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資訊科學研究所

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多 階 訊 號 強 度 之 感 測 網 路 定 位 技 術

A Multiple Power-levels Approach for Sensor Network Localization

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多階訊號強度之感測網路定位技術

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摘　　要

感測式網路(sensor network)這一項技術讓我們可以深入且貼近地觀察一整片地區，目前討論的課題多半著重在感測式節點的繞路、合作與能量消耗等方面。定位系統是無線感應式網路的重要基本功能，然而卻是比較少被討論到的。在本篇論文中，我們將提出一個適合應用在無線感測式網路上的定位方法。我們利用參考點廣播其多階訊號強度，將整個平面分割成許多小區域，感測式節點依照收到訊號的不同來進行定位。在論文中，我們將會討論這個定位方法的極限，並進行模擬測試。根據模擬結果顯示，我們的方法相較於單一訊號強度方法可提供較好的準確度，且這個方法在訊號傳輸距離不穩定、訊號碰撞以及隨機散佈等狀況下皆有不錯的表現，相當適合運用在感測式網路環境中。

A Multiple Power-levels Approach for Sensor Network Localization

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DEPARTMENT OF COMPUTER AND INFORMATION SCIENCE

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Abstract

Sensor network technique enhances our ability to monitor and observe the physical world. Many recently researches for sensor network focus on routing, nodes cooperation and energy consumption. In addition to these topics, localization service is an important function in sensor network system. In this thesis, we will present a multiple power-levels localization algorithm for wireless sensor network. We also discuss the boundary of our algorithm and evaluate the performance in different environment. The simulation results show that our algorithm can reach much better accuracy than traditional single power-level methods. In critical situations such as reference node failure, unstable radio transmission range and beacon collision, our algorithm performs well. We believe that this algorithm is suitable for sensor network.

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Chapter 1

Introduction

Sensor network technique enhances the ability in monitoring and researching the physical world. The wireless tiny sensor nodes can be randomly placed to cover wide area with high density. In the simplest condition, when sensor nodes detect events for our interest, sensor network can create a routing path to the sink node. This event will propagate through the routing path to the sink node. The sink node can collect and save all the events that sensor network detected. Routing protocol is an important topic of sensor network. The design of sensor network is usually based on application requirement, so different routing protocols focus on different concerns. For example, some protocols may concern with path optimization and others may care about the energy consumption. In more complex condition of sensor network, nodes not only manage simple routing but also pre-process, aggregate or summarize events. There are many researches focused on distributed sensor network cooperation, and these researches let sensor network more powerful and more efficient.

Energy consumption is a key challenge through every aspect of senor network. The sensor nodes are too small to supply sufficient energy. In order to reduce the energy consumption and extend sensor network lifetime, every layer of sensor network system must be carefully designed.

Except routing, nodes cooperation and energy consumption, localization is an important characteristic of sensor network. Many applications need detail geographic information. This domain still needs more researches. When spreading sensor nodes randomly over a large area, the localization system is an essential background service of sensor network. The received data can be meaningful only when we know where the data comes from. If every node can know its position, many geographic aware applications can be applied to sensor network. For example, the directional flooding, the geographic aware routing such as Greedy Perimeter Stateless Routing (GPSR) [2] and the region cluster-head dominating algorithm [3].

The Global Positioning System (GPS) [1] is one of solutions of localization problem in outdoor environment. But GPS doesn't design for sensor network, and many properties do not fit sensor network. For example, the energy and computation requirement may exceed the design of sensor nodes. So, there should be a localization algorithm that was designed for sensor network.

In this thesis, the goals of our localization algorithm are shown as following.

1. Simple algorithm: Because the sensor nodes are low computation power and low energy-consumption, the location algorithm should be simple.

2. RF-based: Sensor nodes use short-range radio frequency to communication with others. If sensor nodes can use RF property to locate themselves, they do not need additional equipment. Methods that needs extra antenna or device is unsuitable in sensor network.

3. Low energy consumption: Sensor node's energy resource is limited. Simple algorithm and RF-based method can also save energy. Besides, there are many concerns of energy consumption when system implementation. For example, the message length, the interval of two localization procedure, the listening time, the sleeping time and so on.

4. Match different scale: Sensor network may be used to observe different scale environment, from meters to miles, and the requirement of location accuracy is also distinct. We hope that our algorithm can suit for different scale and accuracy.

5. Randomly spread: Sensor network may be placed regularly. But in most application, sensor nodes spread randomly. The localization algorithm must work well in both regular and random placement condition.

6. Short response time: Localization procedure is just a background functionality of sensor network. Response time needs to be able to within a reasonable time. Lower response time can improve the sensor network performance.

Now, we briefly describe our localization algorithm. In our algorithm, reference nodes (RNs) can be placed regularly or randomly, and their positions are known in advance. RNs would broadcast periodic beacon with multiple power-levels, as r_1, r_2, $r_3 ... r_n$ where $r_{i-1} < r_i$. Each beacon frame contains three information, RN's position, the transmission radius of this beacon and the set of transmission radiuses. When sensor nodes receive beacons, they would summarize beacons from the same RN to estimate the distance between RN to the sensor node. For example, if sensor nodes can only receive beacons which transmission radiuses are r_3, r_4 and r_5. We know the distance between RN is between r_3 and r_2. If sensor nodes can receive beacons from several RNs, sensor nodes also arrange a table that contain all RNs. The sensor nodes can input this table into our localization algorithm to calculate the estimated position.

The key point of our algorithm is the idea of multiple power-level. Traditionally, overlap region algorithm only use single transmission power-level. Using multiple power-levels can divide sensor plane into much more regions, and degree of localization accuracy would increase. We can even adjust the number of level to adapt environment noise condition. We will show the best case of our algorithm, and the relationship between number power-level and average localization error. We compare regular placement and random placement, and also use different radio propagation model to test our algorithm.

Chapter 2

Related Works

There are many localization techniques, using different phenomenon to locate, such as sound wave, IR [8] and so on. These techniques may be unsuitable for sensor network domain, because all of them need additional device to assist the localization procedure. Sensor nodes always use wireless communication to cooperation. So, using radio related method to locate is reasonable. The following localization techniques are based on different radio characteristics. First, we will discuss three major characteristics of radio, Angle of Arrival(AOA), Time of Arrival(TOA) and Received Signal Strength(RSS). After that, we will discuss the existing methods such as overlap regoin and GPS.

2.1 Location-sensing Techniques

Location sensing approaches typically use some characteristics of communication signal between reference nodes(RNs) and mobile nodes(MNs) to estimate the location of MN. In system construction phase, the location of RNs must be known via GPS or other location determining system. According to the information of RNs, MNs can obtain their location by the measurement of communication signal. In the following, we will discuss about three major characteristics of radio.

1. Angle of arrival (AOA): Angle of arrival is commonly used in direction-based systems. When a MN receives signals from each RN, MN can estimate the angle of arrived signal. As shown in Figure 2.1, the position of MN can be computed using triangulation method. This approach requires the installation of complex antenna array at transmitting stations. The complex antenna array is an additional requirement and this technique is inefficient for sensor network. All of AOA methods still need to concern the multi-path effect. AOA is inapplicable for indoor environment or high node density network.

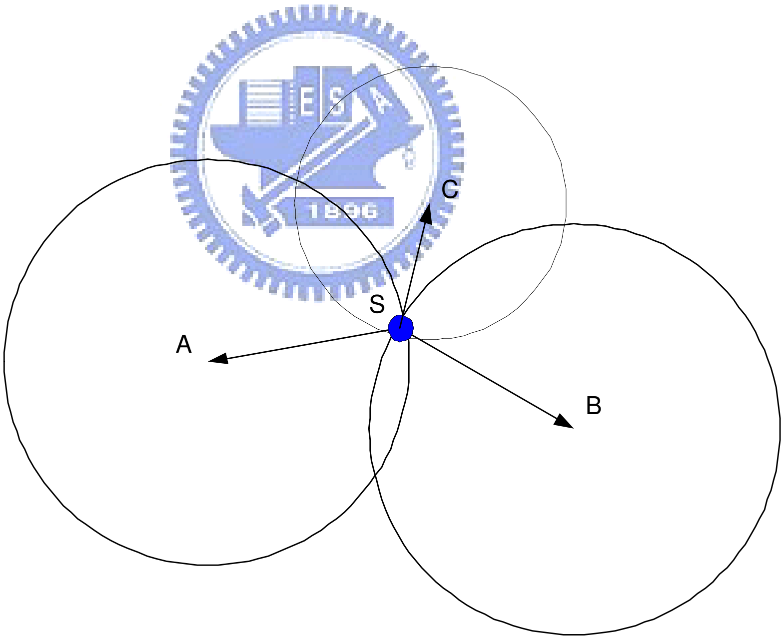

Figure 2.1: The illustration of measuring AOA.

2. Time of arrival (TOA) [1] : The signal propagation time from RN to MN can be measured with a precise time synchronization of RN and MN. Sensor

node can measure the small time, calculate distance between the RN and MN, and compute its location. This technique is similar to sonar system. But the sound speed is less than 500 meter per second and the radio propagation speed is $3 * 10^8$ meter per second. It's hard to measure the radio propagation time from RN to MN, because a small measurement error would cause huge location error. So, the TOA is not suitable for small scale environment. On the contrary, the GPS system which is based on TOA works well in large scale environment.

3. Received signal strength (RSS): Signal Strength is an important characteristic of radio. We can always get RSS value in wireless communication system and use it to estimate MN's location without additional equipment and cost. Many researches focus on radio propagation models, and we can use these models to calculate the distance from receiver to sransmitter. According to the location of transmitters is known, the receiver can compute its location using triangulation method.

   But our experience show that signal strength is very hard to handle, because many factors interfere the RSS value. For example, multi-path, noise, collision, receiver's antenna angle, even humidity, temperature and so on will influence RSS. Since RSS is highly unstable, using simple triangulation method would be over-sensitive. Therefore, some RSS based systems, like signal pattern matching, do not use triangulation method directly.

2.2 GPS

GPS [1] is wide-used global position system, based on TOA technique. It calculates the location by measuring the time and distance between a GPS receiver and at least tree satellites. There are two main problems if the GPS system is used in sensor network.

1. High energy-consumption: In our experience, two 2000 mAh batteries can support GPS device to work continuously for only 3 hours.

2. Unstable for small scale: The accuracy of GPS can reach 5 meters but this is too rough for small scale sensor network environment.

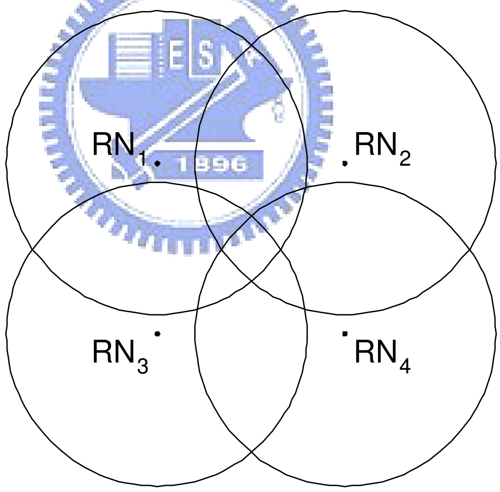

Figure 2.2: The illustration of overlap region concept.

2.3 Location with Overlap Region

Overlap region that was shown in Figure 2.2 is an intuitional method [4]. We can simply image that every reference node's signal can cover a circle. Sensor node can determine the region by received signals. Traditionally, reference node use fixed power to broadcast signal. If we want to refine the region and increase the degree of accuracy, we just use more reference nodes. The characteristic of overlap region method is that nodes in the same overlap region would be located in the same position. We can treat nodes in the same region as a cluster and the cluster-based algorithms can be used in overlap region models.

2.4 Signal Pattern Matching

Recently, many papers focus on signal pattern matching, especially using existing WLAN network. This method needs a database to store the signal patterns that were measured or generated in advance. The location can be obtained by matching signal pattern. A receiver collects the signals pattern that it can receive. Collected signal may not totally match a pattern in database, but we should use some approximate algorithm to produce suitable position. The working flow of signal pattern matching is shown in Figure 2.3.

Generally, there are two kinds of methods to create the signal pattern database. First one is to collect signal pattern information over complete sensor network plane, as RADAR system [7]. This method needs a lot of pre-measurement effort and may be unsuitable for sensor network. Of course, this method would build a very precise signal pattern database. On the contrary, another one is using radio propagation models [6] to generate signal pattern. This method is more appropriate for a plane surface than an in-door environment. It's hard to use radio propagation model to generate signal pattern database in complex environment, because there are too many factors such as material and size of objects, signal reflection, the multi-path effect.

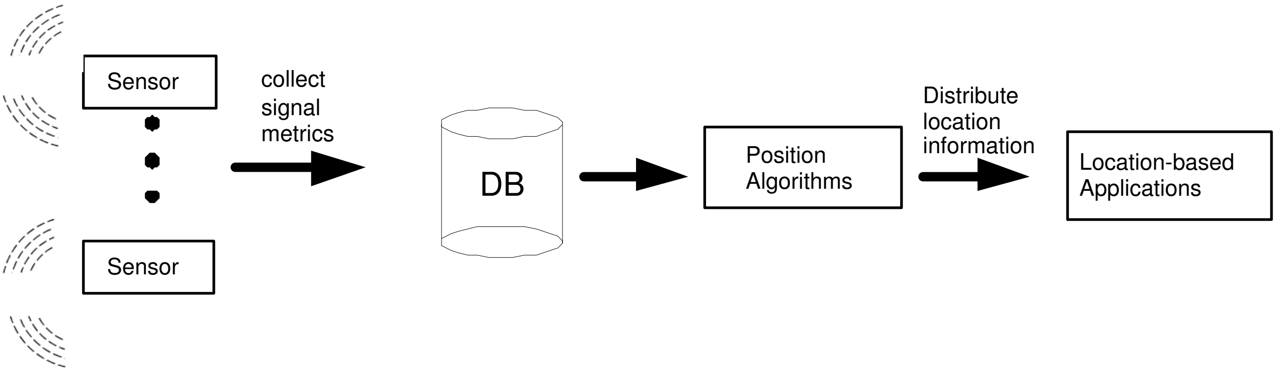

Figure 2.3: Signal pattern matching method working flow.

2.5 Compare Multiple Power-Levels Algorithm with Related Works

Using simple RSS with triangulation method to calculate position is over-sensitive, but using overlap region method is too rough. The signal pattern matching method needs the cost of pre-measurement but overlap region needn't. Therefore, we propose a multiple power-levels localization method that combine the overlap region method and RSS method. Keeping the advantage of overlap region, our method can easily control the degree of accuracy. Keeping the advantage of simple RSS with triangulation method, our method can reduce the noise interference by deciding the number of power level. When noise interference is small, we use more power-levels to increase the degree of accuracy. Reversely, when noise interference is serious, we use less power-levels.

Chapter 3

Multiple Power-Levels Localization Algorithm

In Chapter 2, we present simple overlap region method with single power-level in Figure 2.2. It shows that single power-level forms few distinguish regions. As the number of distinguish region increase, the location accuracy also increase. Therefore, we propose a multiple power-levels localization algorithm as Figure 3.1, to improve the localization accuracy by increasing the number of distinguish regions.

In Section 3.1, we will describe the design of beacon structure. In Section 3.2, we will explain how to collect beacons and how to find the most appropriate radius. In Section 3.3, we will give the localization algorithm in different overlap region conditions. In Section 3.4, we present the out of region condition and the over four overlaps condition.

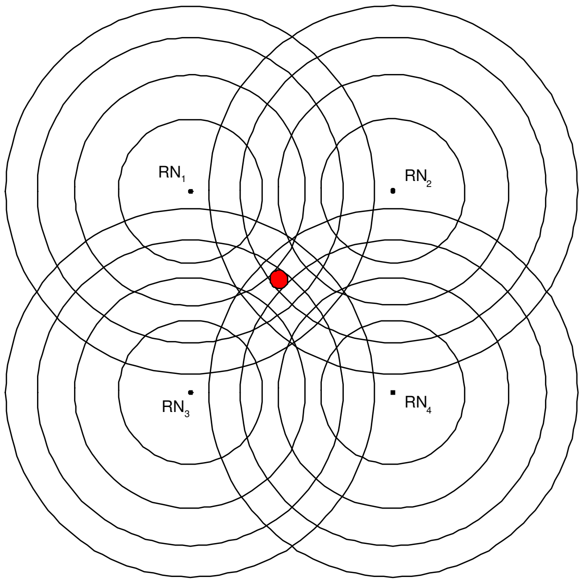

Figure 3.1: The Multiple power-levels overlap region.

3.1 Beacon Structure and Reference Node Broadcast

As we mentioned in Chapter 1, the absolute position of RN is known in advance. The position of MNs can be determined via the periodically beacons that were broadcasted by RNs. The beacon was designed to contain RN's position and transmission range. It's obvious that simpler beacon structure would reduce the transmission overhead. Of course, beacon structure can be changed to match different system if necessary.

In our system, we define the simple beacon structure in Table 3.1. There are three fields on the beacon frame. The first field store the RN's position; the second one store set of radiuses that the RN used; the third one is transmission radius of this beacon.

RN's position (x,y)	All radiuses this RN used	Radius of this beacon

Table 3.1: The beacon structure.

If the environment is almost no noise, we can use more power-levels to divide sensor plain into more regions and increase the position accuracy. For example, the position of RN is in (100,0) and it has five power-levels that are 20, 40, 60, 80, and 99. The RN will broadcast the beacon for each power-level. In the following, the beacon was broadcasted while power-level is 60.

RN's position (x,y)	All radiuses this RN used	Radius of this beacon
(100,0)	20,40,60,80,99	60

If the background noise of the environment is serious, the RSS value is highly unstable. In such condition, using too many power-levels is meaningless, we just use less power-levels. For example, the position of RN is in (100,0) and it has three power-levels that are 33, 66, and 99. In the following, the beacon was broadcasted while power-level is 66.

RN's position (x,y)	All radiuses this RN used	Radius of this beacon
(100,100)	33,66,99	66

3.2 Process Received Beacons

When sensor nodes turn on, sensor node would listen the beacons that were boradcast by RNs and collect them. Then, sensor nodes summarize beacons form the same RN to estimate the roughly distance to the RN. For example, if sensor nodes can only receive beacons from RN(0,0) with transmission radius 60, 80 and 99, as Table 3.2. Therefore, the distance from sensor nodes to RN is between 40 and 60. Finally, we choose 60 as the most appropriate radius and record it. On the other words, we choose the minimum radius of all received beacons as the most appropriate radius.

RN's position (x,y)	All radiuses this RN used	Radius of this beacon
(0,0)	20,40,60,80,99	60
(0,0)	20,40,60,80,99	80
(0,0)	20,40,60,80,99	99

Table 3.2: To summarize beacons from the same RN and find out the most appropriate radius.

Each sensor node maintains a table that contains the position and the most appropriate radius of each RN, as shown in Table 3.3. We use these records as the input data to perform our localization algorithm. It's obvious that if we draw circles according to these records, it would form a overlap region and this sensor nodes should be within.

RN's position (x,y)	Most appropriate radius
(0,0)	60
(0,100)	80
(100,0)	60
(100,100)	89

Table 3.3: Most appropriate radius of every RN, and these records as input data of localization algorithm.

3.3 The Localization Algorithm

According to the data we described in Section 3.2, sensor nodes can calculate their position by using our localization algorithm. The output of our algorithm is the estimated position. We call the distance between real and estimated position as localization error and use the average distance error to judge the performance of localization algorithm.

The localization algorithm that we will present is not the optimal solution. First, the localization algorithm would be use in small sensor node device, so it must be simple and fast. In the complex overlap graph, to calculate precisely centroid of a region is high loading for sensor nodes. Second, in the real world, the main variable that influence localization accuracy is the unstable environment. So, using the optimal solution or approximate solution would not cause a great difference in such environment. By these trade-off considerations, we introduce an approximate solution. We only define one, two, three and four overlaps conditions. When more than four overlaps, we can use four overlaps algorithm to find an approximate solution. Of course people can use more complex method to get more precise solution if necessary.

We will use figures to explain our localization algorithm. In each figure, every circle is the most appropriate radius and the position of RNs is in the center of circles. Assume that the positions of RN A, B, C and D are (x_1, y_1), (x_2, y_2), (x_3, y_3) and (x_4, y_4) and the most appropriate radiuses of RN A, B, C and D are r_1, r_2, r_3 and r_4. The estimated position of our algorithm is O.

3.3.1 One Overlap Condition

The first condition is one overlap condition. Sensor nodes can receive beacons from only one RN. In this condition, the estimated position is determined as the RN's location. In Figure 3.2, sensor nodes set their location just as A's location (x_1, y_1).

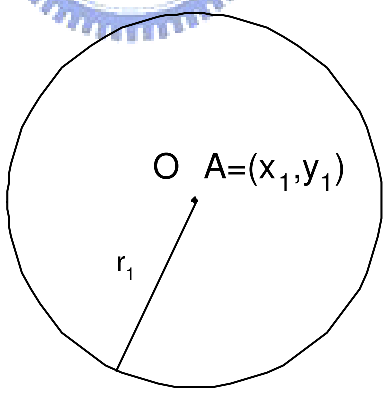

Figure 3.2: One Overlap Condition.

3.3.2 Two Overlaps Condition

The second condition is two overlaps condition. Sensor node can receive beacons from two RNs. As shown in Figure 3.3, sensor nodes should be in the overlap region of circle A and B. We assume that all sensor nodes in the overlap region can be located as point O, the midpoint of line segment L. The Detail is in Figure 3.3.

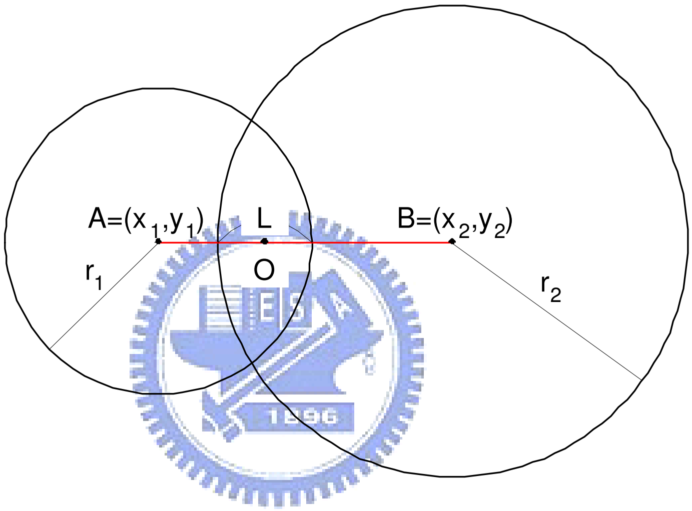

Figure 3.3: Two overlaps condition.

The distance from RN A(x_1, y_1) to O is $dist(A, O)$, where $(\overline{x}, \overline{y})$ is the position of MN.

Let $(\overline{x}, \overline{y})$ is on $\overline{AB}$.

$$dist(A, O) = r_1 - \frac{L}{2} = \sqrt{(\overline{x} - x_1)^2 + (\overline{y} - y_1)^2} \quad (3.1)$$

As we mentioned in Section 3.1, the sensor nodes know the position and radius of RNs A and B via beacon frame. L can be represent as follows.

$$r_1 + r_2 - L = dist(A, B)$$

Therefore, L can be presented as:

$$L = r_1 + r_2 - dist(A, B) \tag{3.2}$$

Then, every point on $\overline{AB}$ can be represent as following.

$$\overline{AB} = \begin{cases} x = x_1 + (x_1 - x_2)t \\ y = y_1 + (y_1 - y_2)t \end{cases} \tag{3.3}$$

According to the equation (3.1), (3,2) and (3.3), we can slove t as follows.

$$\sqrt{(x_1 + (x_1 - x_2)t - x_1)^2 + (y_1 + (y_1 - y_2)t - y_1)^2} = r_1 - \frac{L}{2}$$

$$\sqrt{((x_1 - x_2)t)^2 + ((y_1 - y_2)t)^2} = r_1 - \frac{L}{2}$$

$$dist(A, B)t = r_1 - \frac{L}{2}$$

$$t = \frac{2r_1 - L}{2dist(A, B)}$$

Finally, the position of $O(x, y)$ can be obtained by the following formula.

$$O(x, y) = \begin{cases} x = x_1 + \dfrac{(x_1 - x_2)(r_1 - r_2 + dist(A, B))}{2dist(A, B)} \\ \\ y = y_1 + \dfrac{(y_1 - y_2)(r_1 - r_2 + dist(A, B))}{2dist(A, B)} \end{cases} \tag{3.4}$$

3.3.3 Three Overlaps Condition

The third condition is three overlaps condition. Sensor nodes can receive beacons from three RNs. Of course, sensor nodes should be in the overlap region of RN A, B and C. All sensor nodes in the overlap region can be located as point

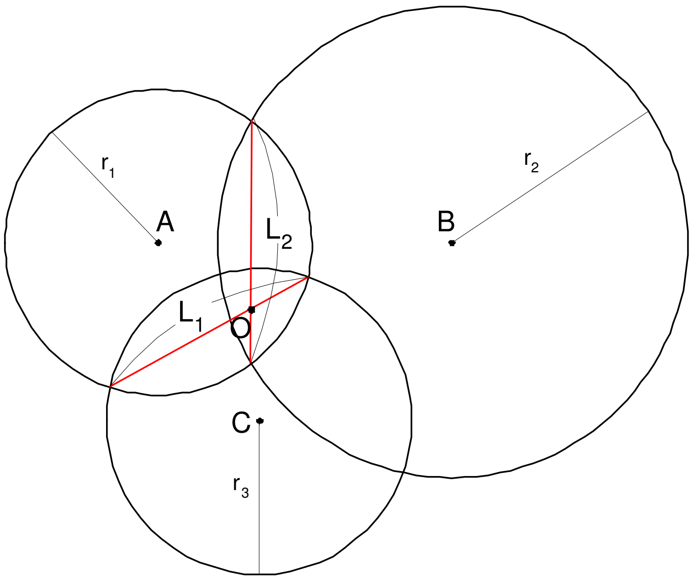

Figure 3.4: Three overlaps condition.

O that is the intersection point of line segment L1 and L2.

As shown in Figure 3.4, the equations of all circles are listing in the follows.

$$\begin{cases} (x-x_1)^2+(y-y_1)^2=r_1^2 \\ (x-x_2)^2+(y-y_2)^2=r_2^2 \\ (x-x_3)^2+(y-y_3)^2=r_3^2 \end{cases} \tag{3.5}$$

The line segment through intersection points of A and C is L_1. The line segment through intersection points of A and B is L_2. The equation of line L_1 is that the equation of circle A subtract equation of circle C. Similaryly, the equation of line L_2 is that the equation of circle A subtract equation of circle B.

$$\begin{cases} L_1:(-2x_1+2x_3)x+x_1^2-x_3^2+(-2y_1+2y_3)y+y_1^2-y_3^2=r_1^2-r_3^2 \\ L_2:(-2x_1+2x_2)x+x_1^2-x_2^2+(-2y_1+2y_2)y+y_1^2-y_2^2=r_1^2-r_2^2 \end{cases} \tag{3.6}$$

We can solve linear equations below and get estimated position $O(x,y)$.

$$\begin{cases} L_1:(-2x_1+2x_3)x+(-2y_1+2y_3)y=r_1^2-r_3^2-x_1^2+x_3^2-y_1^2+y_3^2 \\ L_2:(-2x_1+2x_2)x+(-2y_1+2y_2)y=r_1^2-r_2^2-x_1^2+x_2^2-y_1^2+y_2^2 \end{cases} \tag{3.7}$$

3.3.4 Four Overlaps Condition

The forth condition is four overlaps condition. Sensor nodes can receive beacons from four RNs. In Figure 3.5, sensor nodes would be in the overlap region of RN A, B, C and D. All sensor nodes in the overlap region can be located as point O that is the intersection point of line segment L1 and L2.

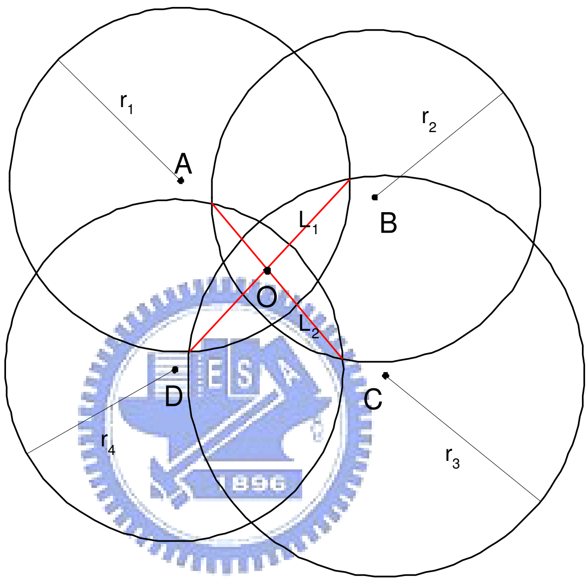

Figure 3.5: Four overlaps condition.

The equations of all circles are shown as following.

$$\begin{cases} (x-x_1)^2+(y-y_1)^2=r_1^2 \\ (x-x_2)^2+(y-y_2)^2=r_2^2 \\ (x-x_3)^2+(y-y_3)^2=r_3^2 \\ (x-x_4)^2+(y-y_4)^2=r_4^2 \end{cases}$$

The line segment through intersection points of A and C is L_1. The line segment through intersection points of B and D is L_2. The equation of line L_1 is that equation of circle A subtract equation of circle C. Similarly, the equation of line L_2 is equation of circle B subtract equation of circle D.

$$\begin{cases} L_1 : (-2x_1 + 2x_3)x + x_1^2 - x_3^2 + (-2y_1 + 2y_3)y + y_1^2 - y_3^2 = r_1^2 - r_3^2 \\ L_2 : (-2x_2 + 2x_4)x + x_2^2 - x_4^2 + (-2y_2 + 2y_4)y + y_2^2 - y_4^2 = r_2^2 - r_4^2 \end{cases} \tag{3.8}$$

Finally, the estimated position $O(x, y)$ is shown as following.

$$\begin{cases} L_1 : (-2x_1 + 2x_3)x + (-2y_1 + 2y_3)y = r_1^2 - r_3^2 - x_1^2 + x_3^2 - y_1^2 + y_3^2 \\ L_2 : (-2x_2 + 2x_4)x + (-2y_2 + 2y_4)y = r_2^2 - r_4^2 - x_2^2 + x_4^2 - y_2^2 + y_4^2 \end{cases} \tag{3.9}$$

3.4 Over Four Overlaps and Random Placement

When more than four overlaps, we basically use the four overlaps algorithm. We also try to find out two line segments, and calculate the intersection point as four overlaps condition. In the regular placement environment, the algorithm that we described works well. But in random placement environment, there are two important concern when choose four RNs to form two line segments.

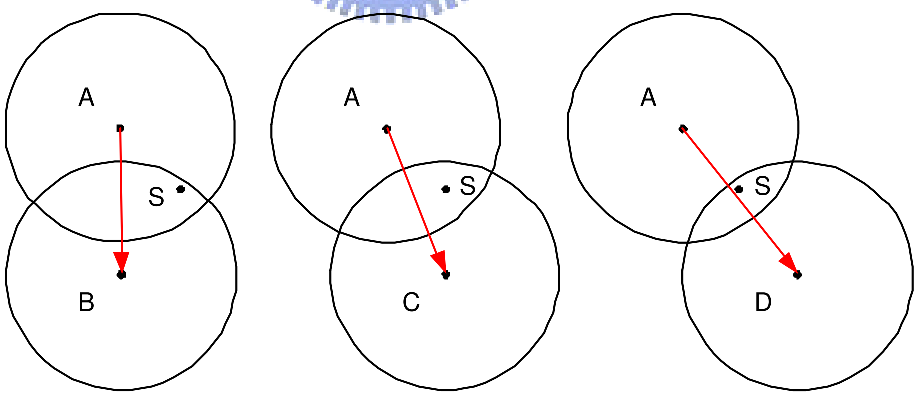

Figure 3.6: Choose RNs that form small overlap region.

First, we observe Figure 3.6, sensor node S can receive beacons from RN A, B, C, and D. We assume that circles are the MAR(most appropriate radius) of respective RN. Obviously, RN A and B form larger overlap region, the average localization error of this region would be great. On the contrary, RN A and C form smaller overlap region, the average localization error of this region would be small. Of course, we should choose a pair of circles that form smaller overlap region and it can increase the accuracy of localization.

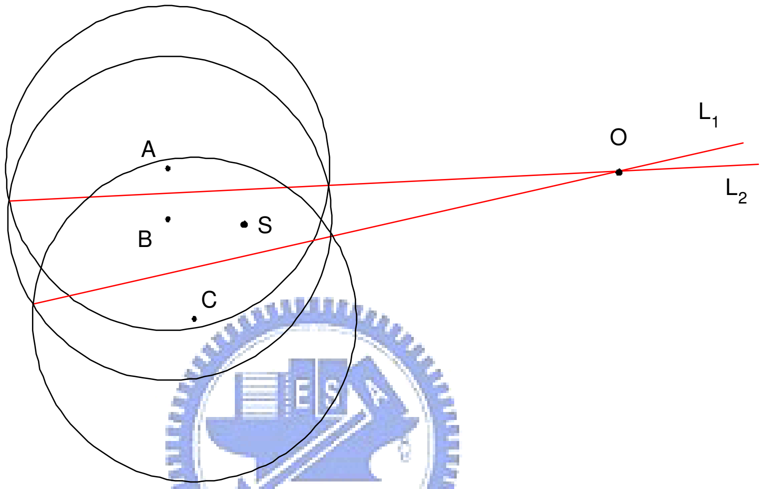

Figure 3.7: The out of region condition.

Second, the worse condition would appear when RNs are very close. A group of close RNs can't provide sufficient localization information. As Figure 3.7, RNs A, B and C are very close. When apply our localization algorithm to this condition, the estimated position O is far away form real position S. We call the problem is out of region problem.

No mater when random placement or over four overlaps condition, we choose four RNs to perform our localization algorithm. We should exclude the out of region problem to avoid great error. And choose a pair of RNs that form smaller overlap region to increase the accuracy of localization. As Figure3.7, in order to avoid the out of region problem, we would back to use two overlaps algorithm to reduce localization error.

Chapter 4

Modeling the Optimal Radiuses Sets

In Chapter 3, we presented our localization algorithm. Obviously, there is a high correlation between accuracy of our localization algorithm and radiuses sets. In this Chapter, we will show an appropriate transmission radiuses set that makes the average error minimum, and also shows average error of our localization algorithm. This transmission radiuses set is the optimal radiuses set. Therefore, we will find out the optimal radiuses sets of different number of power-levels and also try to model the optimal radiuses sets.

We use a testbed that size is the square of 100*100 and each corner place a RN. Assume that there is a sensor node at (x, y) that x and y are integer. So, there are 100*100 sensor nodes in the testbed. Every sensor can calculate the estimated position using our localization algorithm, and also can calculate the error of real position and estimated position. Finally, we can calculate average error over the testbed. The average error can show the overall performance of our localization algorithm.

4.1 The Optimal Radiuses Sets

Assume that RF environment is perfect and each sensor node can get precise a RSS value. Depending on precise RSS records, sensor nodes use our localization algorithm to calculate their estimated position. According to the error of real position and estimated position, system performance will be evaluated. We use the heuristic method to find the optimal sets of radiuses. Assume there are k power-levels with radiuses set R_1, R_2... to R_k, $k = 1, 2...7$. We let $R_{n-1} < R_n$, and R_k is from 1 to 99. By testing all possible radiuses sets, we can obtain the optimal radiuses set that let the average error minimum. The results are shown in Table 4.1. When using 4-levels ($k = 4$), the average error is about 6. When using 5-levels ($k = 5$), the average error is about 5. According to the average error of 4-levels or 5-levels, it's small enough for general applications. When k is larger than 5, the improvement of average error is not remarkable.

In order to model the optimal radius set, we present two possible transmission radius set, the radiuses set of arithmetic progression and the radiuses set of equal area. In Section 4.2, we will discuss the radiuses set of arithmetic progression. In Section 4.3, we will discuss the radiuses set of equal area.

4.2 The Radiuses Sets of Arithmetic Progression

First, we use the radiuses set of arithmetic progression as our power-levels.

Number of level	Optimal radiuses set	Average error
1	(81, 0, 0, 0, 0, 0, 0, 0)	20.096632
2	(62,98, 0, 0, 0, 0, 0, 0)	10.286861
3	(54,79,99, 0, 0, 0, 0, 0)	7.318551
4	(47,69,85,99, 0, 0, 0, 0)	5.868643
5	(37,57,76,89,99, 0, 0, 0)	4.999528
6	(37,54,69,81,91,99, 0, 0)	4.299290
7	(33,48,63,74,83,91,99, 0)	3.713972

Table 4.1: The Optimal Radiuses Sets and Average Error. This table is the boundary of our algorithm.

The proportion of radiuses is:

$$1 : 2 : 3 : 4 : 5....$$

If there are k power-levels, we let $R_k = 99$. By proportion, $r_1 : r_1 : r_3 : ... : r_k$ is $1 : 2 : 3 : ... : k$. We can get the radiuses set of arithmetic progression as our power-levels. The result was shown in Table 4.2.

4.3 The Radiuses Sets of Equal Area

In this section , we will model the optimal radiuses set that we present in Section 4.1. We use the radiuses set of equal area as our power-levels. The radiuses set that let areas of concentric circles graph equal is the radiuses set of equal area.

For example, let the radius of power-levels are r_1, r_2, r_3 and r_4. The annular

Number of level	Arithmetic progression	Average error
1	(99, 0, 0, 0, 0, 0, 0, 0)	31.200766
2	(50,99, 0, 0, 0, 0, 0, 0)	15.225108
3	(33,66,99, 0, 0, 0, 0, 0)	10.557928
4	(24,50,74,99, 0, 0, 0, 0)	8.642663
5	(20,40,59,80,99, 0, 0, 0)	7.174221
6	(17,33,50,66,83,99, 0, 0)	6.027583
7	(14,28,42,57,71,85,99, 0)	5.618708

Table 4.2: The arithmetic progression sets.

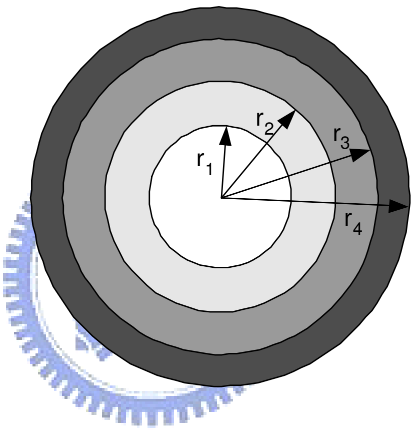

Figure 4.1: The equal area.

area can be represented as:

$$A(r_1) = A(r_2) - A(r_1) = A(r_3) - A(r_2) = A(r_4) - A(r_3)$$

Therefore, the proportion of radiuses is:

$$1 : 2^{\frac{1}{2}} : 3^{\frac{1}{2}} : 4^{\frac{1}{2}} : 5^{\frac{1}{2}}$$

If there are k power-levels, we let $r_k = 99$. By proportion, $r_1 : r_1 : r_3 : ... : r_k$ is $1 : 2^{\frac{1}{2}} : 3^{\frac{1}{2}} : ... : k^{\frac{1}{2}}$. We can get the radiuses set of equal area as our power-levels. The result was shown in Table 4.3.

Number of level	Equal area sets	Average error
1	(99, 0, 0, 0, 0, 0, 0, 0)	31.200766
2	(70,99, 0, 0, 0, 0, 0, 0)	12.995386
3	(57,81,99, 0, 0, 0, 0, 0)	7.861459
4	(49,70,86,99, 0, 0, 0, 0)	6.070294
5	(44,63,77,89,99, 0, 0, 0)	5.261373
6	(40,57,70,81,90,99, 0, 0)	4.424114
7	(37,53,65,75,84,92,99, 0)	3.964617

Table 4.3: The equal area sets.

The average error of optimal, arithmetic progression and equal area radiuses sets are shown in Figure 4.2. It's obvious that the equal area sets are close to optimal radiuses sets when power-levels larger than 4.

Figure 4.3 is a 3D view of our simulation result when use radiuses set 47, 69, 85, 99 and radio propagation is ideal. The Z-axis is the error of our localization algorithm. The maximum errors are near the RNs and the minimum errors are in the four overlaps regions.

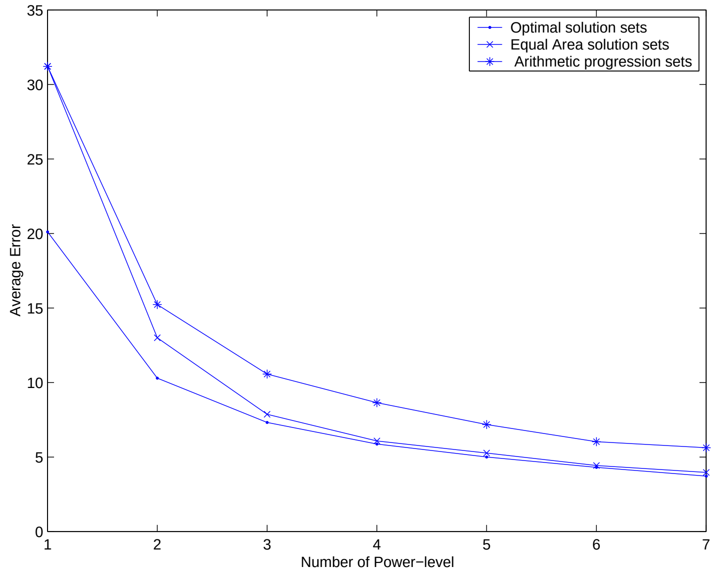

Figure 4.2: The average error of optimal sets, arithmetic progression sets and equal area sets

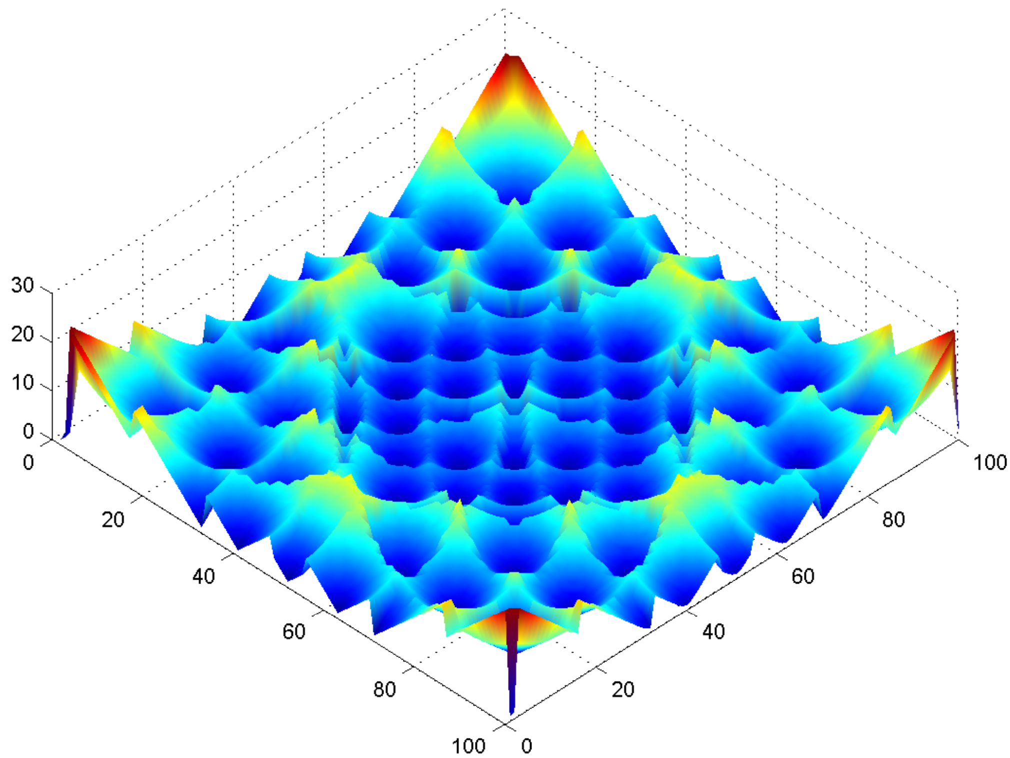

Figure 4.3: The 3D view of ideal condition.

Chapter 5

Simulation Result

In this chapter, we will verify our multiple power-levels localization algorithm. In order to provide a fessible reasonable, suitable and robust localization algorithm, we consider four real condition to show that our algorithm can satisfy the requirement of sensor network.

First, we consider the impact of RN failure. In Section 5.1, it shows that our localization algorithm remain work well under 5% failure rate of RN. Second, we consider the impact of beacon lost. In Section 5.2, simulation result shows that the average error of our localization algorithm is reasonable even thought there is 5% beacon lost. Besides, we consider the impact of unstable radio that approximates to the real world. In section 5.3, we use the shadowing model to simulate the unstable radio signal. Finally, we consider the impact when RNs were placed randomly. In section 5.4, as the number of RN increase, the average error will decrease.

5.1 RN Failure Condition

Any node failure is common condition in sensor network, so we design this simulation. Our testbed is a 1000*1000 test plane and RNs are placed in a regular mesh structure. RNs at every (100*x,100*y) that x and y are both integer. RNs use the set of radiuses, 47, 69 ,85 and 99. We randomly sample 10000 positions in the test plane as the real position of sensor node and calculate the estimated position of them.

Table 5.1 shows the relation of RN failure rate, number of sensor node that can't be located and average error. Because RNs are placed in a mesh structure, every RN is responsible for certain area. Even the failure rate of RNs is 10%, average error is about 12. About 13% sensor node can't be located when the failure rate of RNs is 20%.

RNs Failure(%)	Can not locate	Average error
0%(Optimal)	0	5.868643
1%	2	6.424954
5%	66	8.768633
10%	280	11.91735
20%	1310	18.48232

Table 5.1: The average error when RN failure.

In Figure 5.1, it shows the cumulative probability of errors. In mesh structure, all RNs are deployed to cover the entire test plane. Therefore, the information of all RNs is essential for localization. If the RN is fail, the localization accuracy will certainly become worse. In order to improve it, we can deploy more RNs to increase the overlap degree.

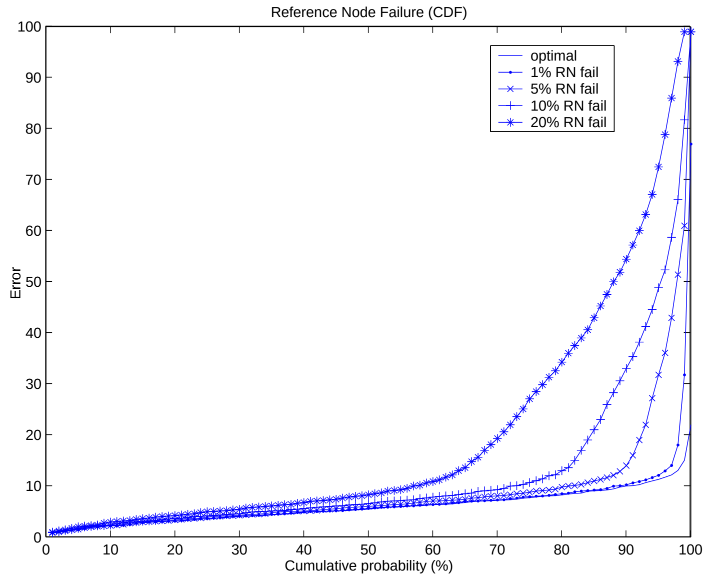

Figure 5.1: The CDF of error when reference node failure.

5.2 Beacon Loss Condition

When RN broadcasts beacons with multiple power-levels, sensor nodes can't receive all of beacons in real case. In our experience, when using simple sensor nodes with simple PHY, the signal collision condition would be serious. All RNs broadcast beacons repetitively and the collision of beacons is unavoidable. We test the beacon loss condition in a 100*100 test plane and each corner deploys a RN with radiuses set, 47, 69, 85 and 99. We also sample 10000 positions in testbed as real position of sensor node and calculate the estimated position of them.

Table 5.2 shows the average error of different loss rate. Even 20% beacon loss, the average error is about 10.65. In Figure 5.2, it shows cumulative probability of errors with beacon loss. Even 20% beacon were lost, 80% error is less than 15.

Beacon loss rate	Average error
Beacon loss 1%	5.868643
Beacon loss 1%	6.091551
Beacon loss 5%	6.989892
Beacon loss 10%	8.16109
Beacon loss 20%	10.65021

Table 5.2: The average error when beacon loss.

In this network structure, all RNs may broadcast beacons at the same time. It will incur the signal collision and localization accuracy become worse. The defect can be solved by utilizing the random backoff or frequency division mechanism of RN to deduce collision condition. We can place more RNs to increase the overlap degree. RN can use random backoff or frequency division to reduce beacon collision. Another solution is that the sensor node can listen for a period of time to collect enough beacons. In system design level, we can use these methods to improve the localization accuracy.

5.3 The Unstable Radio Condition

Ideal radio propagation model does not exist in the real world. In order to test our algorithm, we consider the unstable radio propagation that the propagation shape is not a perfect circle. We use shadowing model [6] to generate the unstable radio propagation model. Assume that RNs are deployed at four corners in a 100*100 test plane. RNs use a set of radiuses, 47, 69, 85 and 99. We sample 10000 positions in testbed as real position of sensor node and calculate the esti-

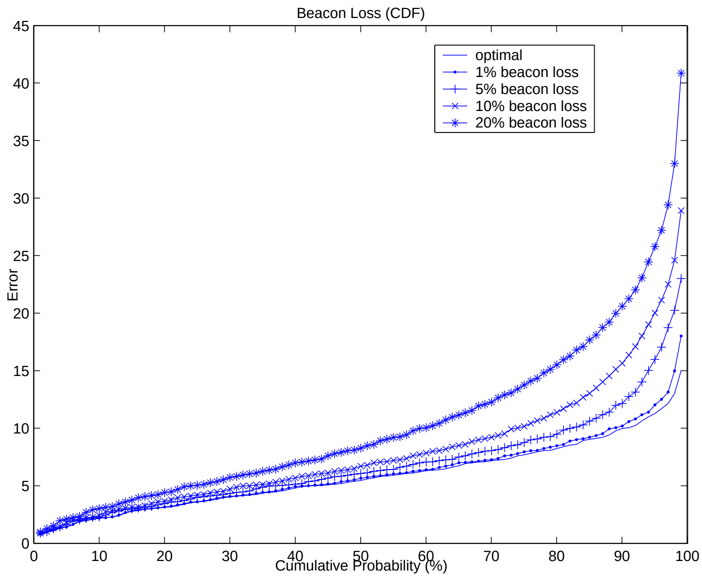

Figure 5.2: The CDF of error when beacon loss.

mated position.

First, the mean received power at distance d, denoted by $\overline{P_r(d)}$. $\overline{P_r(d)}$ is computed relative to $P_r(d_0)$ as follow. It use the close-in distance d_0 as the reference. β is the path loss exponent, and it depends on different environment.

$$\frac{P_r(d_0)}{\overline{P_r(d)}} = (\frac{d}{d_0})^{\beta} \tag{5.1}$$

We can measure it in dB.

$$[\frac{\overline{P_r(d)}}{P_r(d_0)}]_{dB} = -10\beta log(\frac{d}{d_0}) \tag{5.2}$$

The shadowing model is as following. First part is the mean received power as equation (5.2). The second part, X_{dB}, is a Gaussian random variable with zero mean and standard deviation is $\sigma_{dB} \cdot \sigma_{dB}$. σ_{dB} is shadowing deviation, and it also depends on different environment.

$$[\frac{\overline{P_r(d)}}{P_r(d_0)}]_{dB} = -10\beta log(\frac{d}{d_0}) + X_{dB} \tag{5.3}$$

We use shadowing model to simulate the unstable radio propagation. The d_{var} is the unstable propagation distance and d_r is expected propagation distance.

$$\frac{d_{var}}{d_0} = \sqrt[\beta]{10^{\frac{-10\beta log(\frac{d_r}{d_0})+X_{dB}}{-10}}} \tag{5.4}$$

Table 5.3 shows the average error of different deviation. Although the RSS values can vary from −17dB to 17dB, but average error is about 16.

σ_{dB}	95% (dB)	95%d_{var} when $d_r = 99$	Avg. error
1	$-1.96 < x < 1.96$	$88.4 < r < 110.8$	6.39698
2	$-7.84 < x < 7.84$	$63.0 < r < 155.5$	10.05809
3	$-17.64 < x < 17.64$	$35.9 < r < 273.3$	16.74511
4	$-31.36 < x < 31.36$	$16.3 < r < 602.0$	24.0704
5	$-49 < x < 49$	$5.9 < r < 1662.0$	29.97005

Table 5.3: The average error with different deviation, using shadowing model.

Figure 5.3 shows cumulative probability of errors. The average localization error would much larger than RNs failure condition and beacon lost condition. The unstable radio is the main factor of localization algorithm in sensor notwork. When deviation is 3, 80% error is less than 20.

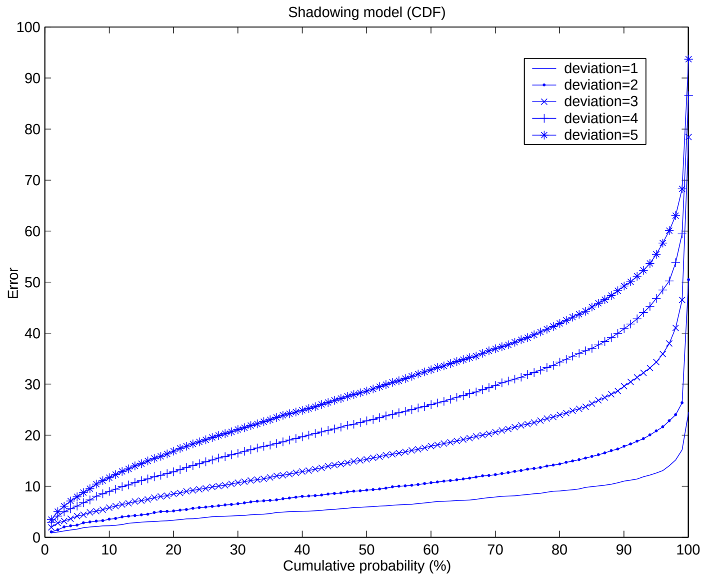

Figure 5.3: The CDF of error when use sadowing model.

5.4 Random Placement Condition

Finally, we consider the impact when RNs were random placement. The testbed is a 1000*1000 plane. We randomly sample 10000 (x,y) where x and y are in the test plane and calculate the average error of all samples. We simulate the different density of RN by place 100, 200, 300, 400 and 500 RNs in testbed. All RNs use a set of radiuses, 47, 69, 85 and 99.

The average error with random placement RN is shown in Table 5.4. When 100 RNs was deployed, the average error is great. Because the RNs are sparse and some place doesn't be covered by any RN. So there are about 722 senor node can not be located. As the number of RN increase, the average error would decrease. We should use as least 300 RNs to cover entire the plane and average error is about 10.

Number of RNs	Can not locate	Average error
100	722	30.92673
200	80	15.53528
300	11	10.06678
400	2	8.248495
500	0	6.956979

Table 5.4: The average error with random placement of RN.

Figure 5.4 shows cumulative probability of errors. When number of RNs is 300, 80% error is less than 10. When more than 300 RNs, the improvement is not obvious.

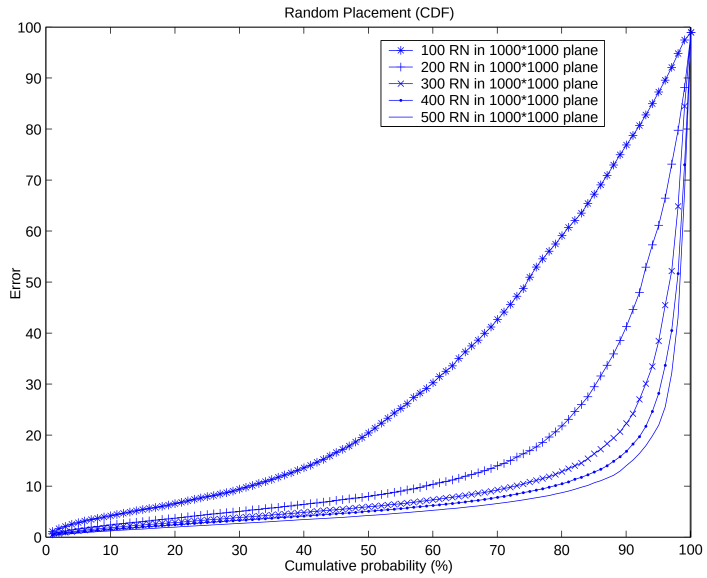

Figure 5.4: The CDF of error when random placement.

There are some simple methods can improve the localization accuracy in random placement environment. First, if many RNs are too close, the overlap region would be large and localization error would be large. We should use some algorithm to control the density of RNs, such as PEAS [5]. The density control algorithm can guarantee the average distribution of RNs. The close RNs can't provide useful overlap condition and even will form out of region condition. Second, sensor node can always receive many RN's beacon when RN density is high. We should choose a pair of circles that form smaller overlap region and it can increase the accuracy of localization.

Chapter 6

Conclusion and Future Work

In this thesis, we present a multiple power-levels approach for sensor network localization. Our method doesn't need additional device and use simple algorithm for sensor nodes. The average error is only 6% when using 4 power-levels in ideal environment. Our algorithm is robust when against RN failure, beacon loss, and highly unstable radio environment. We can also use our localization algorithm in random placement environment.

The key point of this thesis is multiple power-levels concept, this is an interesting idea. Many existing algorithms can be enhanced by multiple power-levels concept. For example, routing algorithm can use multiple power-levels to find out the distance between two sensor nodes. In some power consumption control algorithm, sensor node can use different power-levels depending on its remaining energy. Reference nodes can decide the service range by using multiple power-levels. Anyway, we can use the concept of multiple power-levels to create gradations and adapt to many circumstances.

In fact, there are some interesting issues for multiple power-levels localization algorithm.

1. Providing an efficient method for selecting useful RNs when sensor node can receive more than four RN's signal.

2. Improving the performance of multiple power-levels localization algorithm when RNs are random placement.

3. Combining other algorithms with our localization algorithm, such as density control algorithm and routing algorithm.

4. Building a real system.

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