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碩 士 論 文

基於接收多頻訊號之強度的穩健三點定位法

A Robust Trilateration Positioning Based on Received

Multi-Frequency Signal Strengths

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摘要

在定位系統中，常利用的一種方法是藉由多個已知位置的節點(稱之為參考點)測得目標點的距離後，再利用參考點位置和其所測得距離去做定位。而在測量距離這方面，如果是藉由訊號強度來推算，我們就稱之為使用訊號強度資訊的定位系統。利用訊號在被送出後，其強度會隨著傳送距離的增加而衰減的特性，我們可以用衰減模型計算所接收到的訊號強度的傳輸距離。一般而言，訊號在被送出並且被接收後，其強度在此傳輸路徑上是按照一個路徑衰減指數成指數衰減，因此如果可以獲得路徑上的路徑衰減指數，我們就可以做出精確的距離測量。

但另一方面，即使在同一空間中，卻因為存在著許多變數而導致各個不同的路徑都擁有自己的路徑衰減指數，所以此篇論文我們提出先利用兩個不同頻率的訊號測得參考點到目標上的路徑衰減指數後，再利用此數值做此路徑的距離推導，最後再藉由三點定位法做出目標的定位。而透過二個模擬實驗，可以得知此改善的定位系統可以獲得好的定位精確度。

A Robust Trilateration Positioning Based on Received Multi-Frequency Signal Strengths

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Abstract

Positioning technique is widely used in many applications such as Global Positioning System (GPS). There are many studies concentrated on this issue. Received-Signal-Strength-based (RSS-based) positioning method is one kind of the positioning mechanisms. It uses the received-signal-strength (RSS) information to estimate the distances from reference nodes to the target, and then uses these distance information and the positions of those reference nodes to perform the positioning task.

Therefore, the estimation of the distance between the reference node and the target is the key point which affects the positioning accuracy. In this thesis, we proposed a robust trilateration method to estimate Path Loss Exponent (PLE) which stands for the signal attenuate rate for each reference node to target path by using two different frequency signals and the trilateration method. Then we used every PLE to calculate the corresponding distance and performed the trilateration positioning task using these distances. We also ran two simulations to evaluate our proposed method. The simulation results show that our robust trilateration positioning method is really more precise than positioning methods with fixed PLE for every path.

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Chapter 1 Introduction

1.1 Motivation

The received-signal-strength-based (RSS-based) positioning system is a technology which locates the object by received-signal-strength (RSS) information in the space [23]. And the RSS information is the value obtained by the position-unknown target of the received signal that is emitted by the position-known reference node in this system. By the characteristic that the signal strength from the transmitter to the receiver (T-R) is decreased follows the increase on the T-R distance and the attenuation of the signal strength can be described as the propagation model, we can calculate the T-R distance by the RSS information. Moreover, we can calculate the more accurate T-R distance by the absolute model [23]. And in the positioning system, we estimate a target's position by some positioning methods like trilateration when getting sufficient information about T-R distances. So in the positioning step in detail based on the above concept, first we let at least 3 reference nodes as transmitters send signals out to the space. Then the target as the receiver on the same space obtains signals and instantly measures all RSSs. And all T-R distances can be calculated by these RSS information and the corresponding equation. Finally, the target's location is calculated by the positioning method.

In the above system, we can find that the key point in the step is how to get satisfied T-R distances for positioning. In other words, this issue is regarded as how to calculate the correct T-R distance by the absolute RSS-to-distance equation. On the theory, the RSS-to-distance equation for calculating T-R distance can be derived by all known information. And we ought to get a completely exact distance value by the RSS information and the absolute equation. However, the general experimental measurements usually indicate that the signal strength attenuation is the distortion in reality so the RSS information or the RSS-to-distance equation may be false. Especially in the confused environment, the signal strength from T-R is nearly out of the rule. This phenomenon is resulted in by many causes, and most of these causes are from the radio propagation's physical characteristics.

Some physical states are occurred when there are some objects in the space and the signal from the transmitter meets the objects on the line of T-R. Such as absorption, reflection, diffraction, scattering, and etc may be occurred, and we can call the phenomena fading. The receiver usually gets the incorrect RSS which is smaller than the normal state in general case after these effects. Moreover, even the objects are not on the line of T-R, they usually influence measuring RSS. The phenomenon is called multipath, and it is also a significant impact on the radio propagation.

Due to these problems, there are some proposed distinct methods of distance calculating which are different from the RSS measurement wanting to solve them, such as Angle of Arrival (AOA), Time of Arrival (TOA), and Time Difference of Arrival (TDOA). In general, some of methods really increase the accuracy of measured distance, but they also come with other costs such as the expensive equipment. So the advantages of the RSS-based positioning system are cheap and easy to implement although the disadvantage is that it has the lower accuracy.

And in respect of the positioning method, trilateration is one of the most famous schemes. Most of the range-based systems use it to achieve positioning. Trilateration presents a good performance in the clear environment. However, in the confused environment it may get the terrible position because of the inaccuracy range. And the reason is also because of the error rate of T-R distances. So getting the accuracy T-R distance becomes the most critical point for the RSS-based trilateration positioning.

As a result of the accurate distance measurement, we have to focus on the RSS-to-distance equation. The issue what we mention above about the signal strength attenuation rate, which we called path loss exponent (PLE), is one most important factor for the RSS-to-distance calculation. And with the more precise PLE, we can calculate the more precise T-R distance. In generally, the distance calculation in one space uses the same PLE. However, in practice every T-R path has its own PLE for its propagation process even in the different times. So in this thesis, we use two signals with different frequencies to calibrate PLEs for all T-R paths for doing distance calculations. By some studies, it can be found that the signal with the greater frequency attenuates faster than the smaller one in the free space or when encountering the obstacles. However, the signals with different frequencies still have the approximate PLE in the same T-R path in the same time. Based on this concept, we propose a method to let all reference nodes emit two signals with different frequencies to the target, and then use all RSS information and trilateration to estimate the suitable PLE for every T-R path. Hence we use every PLE of different T-R paths and its corresponding RSS to calculate all T-R distances. Finally, we can do the accurate positioning by the more accurate distances and trilateration.

Besides, there are two models for the positioning system, one is the reference node be as the transmitter and the target be as the receiver, the other model is the reference node be as the receiver and the target be as the transmitter. In general, the two models are the same approximately. And in thesis, we all use the former model.

1.2 Thesis Organization

In chapter 2, the radio propagation phenomena are introduced first. We describe all effects which the signal may suffers when traveling in the space. And the corresponding radio propagation models are also on listed. Further, we show the basic trilateration positioning method.

Chapter 3 describes the related work. First, we mention about some papers which are the studies of the RSS-based positioning system and the factors affecting the positioning. And we also introduce some improved RSS-based positioning methods and their evaluations. Finally, some works related to PLE estimation and their usages are introduced.

Chapter 4 is the proposed scheme. First we describe the discovery and the reason about our proposed method for calibrating PLE by two signals with different frequencies. And we write our robust trilateration positioning method step by step. Moreover, we present three special states in our proposed method and some ways to solve them.

Chapter 5 is the simulation result. We first describe the simulation environment and two simulations. Then we show and evaluate the simulation result and discuss the outcome and the performance after finishing two simulations.

Finally, Chapter 6 concludes the thesis and brings the future work.

Chapter 2 Background

2.1 Radio Propagation Phenomena

2.1.1 Free Space Path Loss

In the wireless telecommunication, if the signal propagates as a straight line from T-R, we call it line-of-sight (LOS). Moreover, all signal propagations are LOS in the theoretical model. But in reality, some signal propagations don't tour as LOS so non-line-of-sight (NLOS) is presented. NLOS describes that the signal from the transmitter doesn't travel to the receiver with the straight line but some other paths. Generally, most reasons of NLOS are caused by obstacles. Because of some physical characteristics, the signal may be absorbed or its direction may be changed. Especially in the extreme hostile atmosphere, NLOS is taken place commonly. The diagram of LOS and NLOS phenomena is showed in Figure 1.

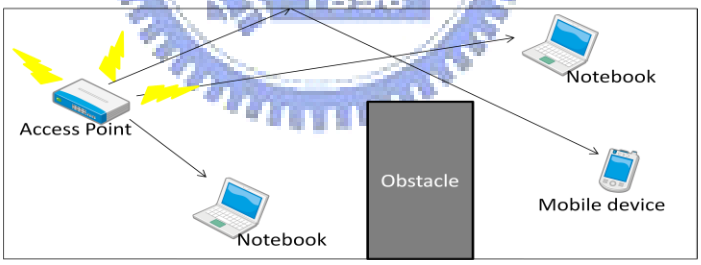

Figure 1: LOS and NLOS phenomena

Free space path loss is the signal strength attenuation process from the isotropic transmitter to the receiver through LOS. And it needs that the radio space is not with the confused physical state and no obstacle or the unstable atmosphere causes the interference. By free space path loss, the signal strength attenuation is in approximate theory and easily derived because its propagation is like a sphere. The most used free space path loss model is Friis transmission equation which is showed in equation (1) where the variables P_t is the transmitted power in the transmitter, P_r is RSS in the receiver, G_t and G_r are antenna gains, λ is the signal's wavelength, and d is the T-R distance. The equation describes that signal strength and the square of the distance are the inverse proportion with each other when others variables are fixed. This relationship of inverse proportion also exists between the signal strength and the square of the signal's wavelength when others variables are fixed.

$$\frac{P_r}{P_t} = G_t \times G_r \times \left(\frac{\lambda}{4 \times \pi \times d}\right)^2 \quad (1)$$

2.1.2 Multipath

In the radio propagation, the multipath effect is the phenomenon that the signal from the transmitter reaches the receiver by two or more paths. Due to this effect, the receiver gets the incorrect signal information and the failure distance calculation by the RSS measurement may be occurred. Reasons of multipath include atmospheric disturb, obstacles' reflection, refraction, and scattering, and etc. Figure 2 shows the transmission of multipath in the space.

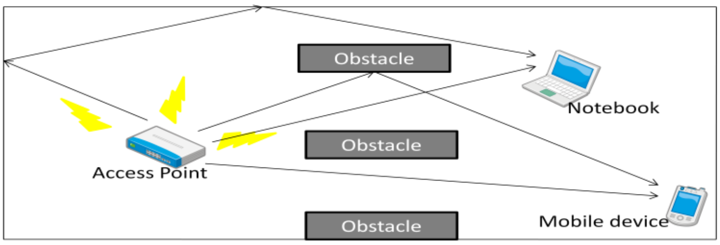

Figure 2: Multipath propagation

The effects of the multipath may be constructive or destructive on the RSS information. Some signals aid the direct path and constructively reinforce the signal, and others subtract from the direct path and destructively interfere with the signal. In other words, when there are many paths from one signal transmission to the target, the actual RSS on the target is the sum of all signals' vector from those paths.

The multipath effect causes some errors and impacts on the quality of communications. Therefore, some methods were proposed to solve this problem such as Equalizers. Orthogonal frequency division modulation (OFDM) and Rake receivers are often be used.

Although multipath is one deep impact of the radio propagation, it may be one way to transmit the signal. When the situation is the hard object lies in the straightway from T-R so that the signal can't pass through it, the signal just can travel to the receiver by the multipath effect. This is what we mention about NLOS in the above issue.

And in the positioning system, multipath effect also has the deep impact on the time-based method. Because of multiple paths from the source to the destination, the receiver may not determine the path which is the straight one. On the other hand, multipath affects the RSS-based positioning, too. When one signal arrives the receiver at the same time with some different signals arrive by multipath, RSS may be stronger or weaker in terms of the construction or the destruction of two signal phases.

2.1.3 Fading

In the wireless communication, the fading effect is the signal strength attenuation process which occurs when there are objects on the line between the transmitter and the receiver. Indeed, when the signal experiences some obstacles such as solid or liquid media in particular, the fading effect appears because of physical characteristics like absorption or reflection. The fading effect can be seen as the attenuation rate and it varies with the position and the time in the space. And on the other hand, the radio frequency of the signal also decides the fading effect. In general, the signal with the higher frequency comes with the faster signal strength attenuation in general. However, the real fading progress is hard to estimate and the fading model is usually the random process with a specific attenuate rate. So it usually uses large scale RSS data from one transmitted signal with fixed power to derive the proper model or the equation in the current environment.

The fading effect is the most impact on the RSS-based positioning system. Due to its imprecise quantification and random characteristic, it always affects the RSS measurement between every T-R link. Generally, fading can be divided into some typical types by specific factors. For example, if Doppler spread or coherence time of the channel is considered, there are slow fading and fast fading (time-selective fading) are discussed. And when delay spread or coherence bandwidth of the channel is considered, frequency-selective fading and flat fading are discussed. The following paragraphs introduce these fading types in detail.

Slow fading occurs when coherence time is huge relative to delay constraint through the channel. In this situation, the radio amplitude (signal strength) and the phase change imposed by the channel. And they also can be considered approximately a constant over the period. Fast fading arises when coherence time is small relative delay constraint through the channel. The signal strength and the phase change imposed by the channel in this situation, and they vary very fast like multipath over the period. In other words, fast fading refers to that the fluctuations of signal strengths are violent in the short distance.

Flat fading means that coherence bandwidth is huge relative to bandwidth through the channel. In this situation, signal strengths with different frequencies have the same attenuate rate. On the other hand, frequency-selective fading is that coherence bandwidth is small relative bandwidth through the channel. And when encountering frequency-selective fading, signal strengths with different frequencies experience irrelevant attenuates.

2.1.4 Doppler Effect

The Doppler Effect, which is also called Doppler shift, is the phenomenon that the frequency or the wavelength of the signal changes when the transmitter moves and emits the signals simultaneously. This effect is commonly occurred when the vehicle (transmitter) sounds a siren and approaches, passes, and recedes from the observer (receiver). And comparing to the source frequency, the frequency of the received signal will be increased during the approach, identical at the moment of the pass, and decreased during the recession.

Because the frequency of the signal is the consideration of the RSS-to-distance calculation, the Doppler Effect may influence it. But when we just locate the static target in the positioning system, the effect is not considered necessarily. However, it is better to reference Doppler Effect for doing preferable positioning in the tracking system because the target moves actively.

2.2 Received-Signal-Strength-Based Distance Measurement

The signal strength is the value measured in W (watt) or mW (milliwatt). Generally, we usually take mW as the principle to measure the signal strength. Moreover, the value in mW can be converted into the value in dBm by equation (2) where *P* is the signal strength in mW.

$$\mathrm{dBm} = 10 \times \log \frac{\mathrm{P}}{1\mathrm{mW}} \tag{2}$$

The RSS-based distance measurement, which is the distance calculation, uses the characteristic that the signal strength attenuates with the propagation distance increases. However, the signal transmission in reality is difficult to model as the equation exactly. The channel performance varies with the space, the time, and the equipment. In other words, the progress of the radio propagation is complex because it needs to deal with effects of various physical phenomena, multipath, and fading. Nevertheless, the RSS-to-distance equation still can be derived by the theoretical model. And the model also can access the better simulation by adding some random variables or changing some factors. By this concept, three models which are the most used for path loss, multipath, and fading (which is also called shadowing) are introduced. And all equations show the relationship between the distance and RSS.

First model is the path loss model. In section 2.1.1, equation (1) shows the theoretical model which is the model of free space path loss. And it can be found that PLE in this model is 2 because the isomorphic radio emission without any destruction is just like the sphere. Based on this model, the improved equation (3) is proposed for the path loss model by changing PLE which is the value *n* in the equation. The different PLEs means the different attenuate rates of the T-R path, and it can be considered that every T-R path has its own PLE because of varied conditions. As a result, the path loss model is more real for the RSS-to-distance calculation by the dynamic value of PLE. And some typical PLEs are listed in Table 1 [25].

$$\frac{P_r}{P_t} = G_t \times G_r \times \left(\frac{\lambda}{4 \times \pi \times d}\right)^n \quad (3)$$

Table 1: Some typical values of PLE

Environment	**Path loss exponent**
Outdoor free space	2.0
Outdoor shadowed	2.7 ~ 5.0
Indoor Line-of-sight	1.6 ~ 1.8
Indoor obstructed	4.0 ~ 6.0

The second model is for multipath. In this model, it considers that the transmitter and receiver both are put on the ground and two heights of antennas from the ground result in multipath. So the antenna height h_t from the ground to the transmitter and h_r to the receiver are acquired in the model. By these significant parameters, equation (4) is derived.

$$P_r(d) = \frac{P_t \times G_t \times G_r \times h_t^2 \times h_r^2}{d^4 \times L} \qquad (4)$$

The last most used model is for shadowing which is very difficult to model as the equation. Equation (5) is one most well-known model for shadowing where $PL(d_0)$ is the RSS measurement in short distance d_0 and X_ρ is one random Gaussian variable which has some typical values in Table 2 [25]. Because of many unexpected conditions in the shadowing surrounding, this random variable is used for attempting to construct the equation more realistic. And PLE which is the value n also exists for suiting the environment.

$$PL(d) = PL(d_0) + 10 \times n \times \log\left(\frac{d}{d_0}\right) + X_\rho \qquad (5)$$

Table 2: Some typical values of shadowing deviation

Environment	$\mathbf{X_\rho}$ **(dB)**
Outdoor	4 ~ 12
Line-of-sight in factory	3 ~ 6
Obstructed in factory	6.8
Hard partition in office	7
Soft partition in office	9.6

In addition to above models, there are many radio propagation models were proposed for getting more accurate calculation or being more fitting on specific environments. For example, Rayleigh fading is the well-know outdoor model for the environment which has the multipath effect and impacts of obstacles. And Rician fading model is also the noted model for indoor space. However, we usually use those three models to calculate distance in general.

2.3 Trilateration Positioning Method

Trilateration is one of the most famous range-based positioning methods. In the positioning system, range-based means that it needs the distance information to locate the object. And on the contrary, we call the positioning method without the distance information range-free. In general, the range-based method is more precise than the range-free but requires more expensive devices.

Trilateration basically uses at least three reference nodes' positions and their estimated distances to the target to do positioning. So for doing trilateration, we first need to measure all T-R distances. And after we get these distance information, we can take all transmitters' positions be centers and their corresponding estimated distances to the target be radiuses to draw cycles. As the result, we can get many cycles and the intersection area which these cycles intersect. In the theory, when the receiver gets all theoretical RSS information, we can derive all accurate T-R distances actually. And therefore, it can be found that the intersection area is a point which is the true position of the target. This trilateration diagram is showed in Figure 3.

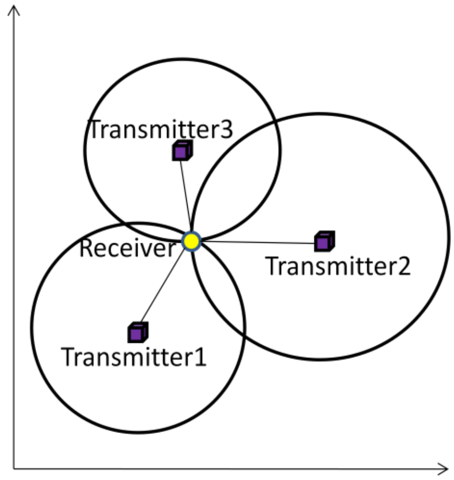

Figure 3: Theoretical trilateration positioning

However, the intersection is usually not a point but an intersection like Figure 4 in practice. Due to phenomena of the radio propagation, the receiver rarely calculate absolute precise T-R distances with inaccuracy RSS information and the unsuitable RSS-to-distance equation. Therefore, the most important problem in this situation is estimating a position which is the closest to the target's real location in the intersection. Maximum Likelihood method which is equation (6) is the most used formula to find the best position. In the equation, (x,y) is the to-be-estimated position, (x_i,y_i) is the position of transmitter i, and r_i is its estimated T-R distance of transmitter i to the receiver. And when we get the smallest value in $\sigma_{x,y}$ from all to-be-estimated positions, the best position is acquired.

$$\sigma_{x,y} = \left|\sqrt{(x-x_1)^2+(y-y_1)^2}-r_1\right| + \cdots + \left|\sqrt{(x-x_i)^2+(y-y_i)^2}-r_i\right| \qquad (6)$$

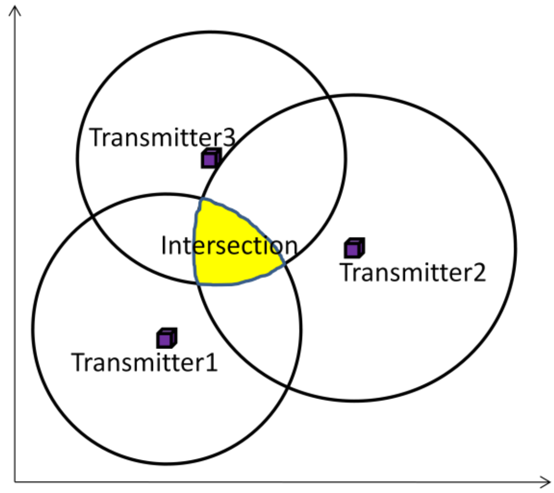

Figure 4: Practical trilateration positioning

Chapter 3 Related Work

3.1 Impact Factors on Received-Signal-Strength-Based Positioning

In the real world, there are many factors affecting signal propagation so we usually get the false RSS information in practice. And the false information makes the impact on the corresponding application and experiment [1]. Moreover, the RSS-to-distance measurement and the RSS-based positioning system get the inaccuracy result in this situation. Most of these impact factors are related to the environment and sensing devices, and it is very difficult to wipe them out absolutely. However, because the RSS measurement is cheap and easy-implementation, there are still a lot of studies and products concentrating on this issue. Part of researches tried to find elements which have impacts on the RSS measurement in different environments and various states [4] [5] [6] [13]. Actually, because physical factors are too hard to eliminate and improve, most studies attempted to enhance the positioning method or the algorithm for achieving the accuracy positioning.

In [4], it analyzed some sources of the signal strength's variability and divided them into two groups, which are factors related to the sensor and factors related to the environment, to discuss. In the aspect of factors related to the sensor, there are RF frequency, antenna orientation, variation of the transceivers, and transmission power. The experimental result showed that every factor related to the sensor above is important in the RSS measurement. On the other hand, the factors related to the environment are specific of the environment and height from the ground. The experimental result also showed that both two factors have the deep impact on the experiment obviously.

In [5], it proposed three important characteristics of the RSS measurement which are effective noise, attenuation rate, and effective range. It used these three properties to evaluate some factors, and it found that the elevation, vegetation, transmission power, packaging, and indoor environment are the important factors of the RSS measurement.

In [6], it also said that antenna characteristics and orientation, variation of the transmission power, and the variation of the frequency are the substantial considerations in the RSS-based positioning system. As a result, it proposed the adaptive test for localization experiments and distance measurements. And it described that choosing the appropriate transmission power is very important.

3.2 Improved Received-Signal-Strength-Based Positioning

There are many proposed methods for the RSS-based positioning system [9] [10] [11] [12] [16]. Indeed, increasing the target's estimated accuracy and decreasing system's consumption are the goal for most proposed methods and systems. So those studies usually exhibit that the estimated accuracy of their proposed methods is increased or the consumption of their systems is decreased. And most of their experimental results showed their declarations are true. The following lists one improved method in detail because the method by frequency diversity is like our concept of multi-frequency.

Frequency diversity is the well-known technique for using to obtain the better signal in the wireless system. In [9], it used this concept to choose the strongest RSS from 11 signals of 11 available channels in 802.15.4 specification. After choosing, it took the selected RSS to do probabilistic and deterministic location schemes. And in the end, experimental results exhibited that the proposed method improved 18 - 23% in average location error.

3.3 Path Loss Exponent Calibration and Usage

There are some studies aimed to get the suitable PLE for environments [3] [7] [17]. In section 2.2, we describe equations of propagation models and the most important variable PLE in those models. PLE is the mainly attenuate rate and the premier factor which affects the RSS-to-distance calculation. In fact, every T-R path in the real space has its own PLE because there are some different causes of the attenuation affecting the signal on its propagation path [2]. As the result, getting more precise PLE means that it can obtain the excellent result in the RSS-to-distance calculation and the RSS-based positioning system [18].

In [2], it proposed that every T-R link has its own PLE, and it used this concept to do the localization. Simulation results showed that the proposed method achieves more precise localization than the method which uses the same PLE on all T-R paths. But the proposed method also had worse performances when PLE in the space is normal distribution or all PLEs are close to each other.

In [7], it presented the method in wireless sensor networks for online calibration on PLE by using Cayley-Menger determinant without distance measurements. And this method only used the RSS measurements and the geometric constraints associated with planarity to estimate PLE. Moreover, because the noise in the RSS measurement may cause a huge bias, the pattern matching scheme was used for approximately correcting the bias. Otherwise, the empirical observation presented that the relationship between mean of all PLEs, standard deviation of RSSs, and all PLEs is nearly independent of the shape of the area in which vertices of quadrilaterals are located and is also independent of the distribution of vertices of quadrilaterals.

Chapter 4 Proposed Approach

4.1 Different Frequency Signals with Dynamic PLE

In reality, every T-R path or possibility link in the area all has its own PLE or attenuation rate at a time. However, it is very difficult to calibrate the fully certain PLE without the absolutely certain distance and its corresponding certain RSS. And in the positioning system, the goal is also getting the right T-R distances for estimating the target's position. So if we can calculate every T-R distance with the precise PLE, we can get the precise T-R distance and the precise positioning result. In this section, we will introduce the scheme about how to use two signals with two different frequencies to calibrate PLE of one T-R path. Then we can calculate each T-R distance by its PLE and use these distances to do positioning.

There are some different characteristics between two signals with distinct frequencies. In general, the strength of higher frequency signal attenuates faster than the lower one when they are propagated through the same T-R path. This phenomenon is formally presented to the model by equation (3).

On the theory, the attenuate rates or PLE through the same T-R path are the same for all signals with different frequencies without some specific states. As the result, we can derive PLE by some signals with different frequencies as following scheme. First we assume that two frequency f_1 and f_2 are emitted to the receiver by the transmitter with T-R distance d, attenuate rate (PLE) *ple* and transmission power S. We also assume that f_1 is lower than f_2, and RSS information with f_1 and f_2 in the receiver are S_1 and S_2. Next we derive equation (7) from equation (3) for the RSS-to-distance calculation. Furthermore, equation (8) is derived because wavelength λ is the value which velocity of light divided by frequency and c is the constant of velocity of light. By equation (8), two distances d_1 and d_2 are calculated by equation (9) and equation (10). We count the distance difference *diff* by equation (11) with different values on *n* iteratively. After calculations, we can find that d_1 and d_2 are the same when the value of *n* equals *ple*. In other words, we can consider that the value of *n* is real PLE of this T-R path when *diff* equals 0.

$$d = \sqrt[n]{\frac{P_t G_t G_r}{P_r}} \times \frac{\lambda}{4\pi} \tag{7}$$

$$d = \sqrt[n]{\frac{P_t G_t G_r}{P_r}} \times \frac{c}{4\pi f} \tag{8}$$

$$d_1 = \sqrt[n]{\frac{S G_t G_r}{S_1}} \times \frac{c}{4\pi f_1} \tag{9}$$

$$d_2 = \sqrt[n]{\frac{S G_t G_r}{S_2}} \times \frac{c}{4\pi f_2} \tag{10}$$

$$diff = |d_1 - d_2| = \left| \sqrt[n]{\frac{S G_t G_r}{S_1}} \times \frac{c}{4\pi f_1} - \sqrt[n]{\frac{S G_t G_r}{S_2}} \times \frac{c}{4\pi f_2} \right| \tag{11}$$

Figure 5 shows the theoretical relationship between different PLEs and distance differences. And distance calculations of two signals are with frequencies 914MHz and 2.4GHz, different PLEs, and RSSs counted by equation (3) with *n* is 2 and *d* is 50 meter. We actually find that the difference between two distances is 0 when PLE is 2.

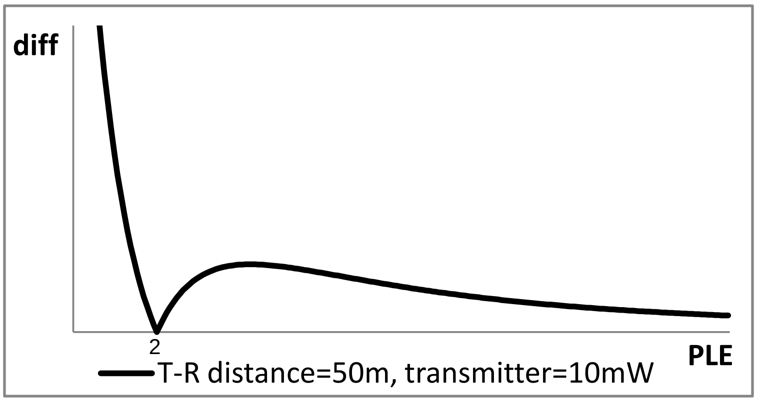

Figure 5: Relationship between PLE and distance difference when real PLE is 2

But in practice, although two signals with different frequencies attenuate with the close same rate through the same T-R path, both two signals may have random interferences so their RSSs are not theoretical values. Therefore, PLE which is calculated by the above method may be deviation and the incorrect T-R distances are possibly calculated. So in our proposed scheme, we not only estimate PLE by above method but solve the problem by adjusting PLE by trilateration.

4.2 Robust Trilateration Positioning Method

Robust trilateration positioning method will be introduced in this section in detail. First we need to construct the environment where all RSS information from every T-R can be collected. We assume that there are at least three reference nodes as transmitters T_1, T_2, …, T_n ($n \geq 3$) with positions (X_1, Y_1), (X_2, Y_2), …, (X_n, Y_n), the target as the receiver R_1 with the position (X_0, Y_0), and all real T-R distances are d_1, d_2, …, d_n. Following subsections will describe this method with explicit steps by the scenario.

4.2.1 Multi-Frequency Signal Strengths Measurement

In this step, we gather all RSSs from all transmitters to the receiver. At the beginning, every transmitter in the space emits two signals with frequency f_1 and frequency f_2. And frequency f_1 is smaller than frequency f_2 so it means that wavelength λ_1 with frequency f_1 is greater than wavelength λ_2 with frequency f_2. Then RSS information what the receiver gets from transmitters T_1, T_2, …, T_n with two frequencies are $S_{1,1}$, $S_{1,2}$, $S_{2,1}$, $S_{2,2}$, …, $S_{n,1}$, $S_{n,2}$ in order.

Based on the characteristic of the radio frequency in normal, RSS from the smaller frequency signal is usually greater than RSS from larger frequency with the same transmitting power and the same distance. It means that we can observe that $S_{x,1}$ is larger than $S_{x,2}$ where x is the number of the transmitter. But in some conditions, RSS from frequency f_1 is smaller than RSS from frequency f_2. We will discuss this specific situation in section 4.3.

4.2.2 Dynamic PLE Calibration for Each T-R Path

By section 4.2.1, the information what we get from the receiver are RSS of all T-R paths with every transmitter which provides two data from two signals. In this step, we estimate PLEs for all T-R paths by these RSS information. And after these PLE calibrations, we calculate all T-R distances by equation (8) and use trilateration to count more suitable PLEs for all T-R paths.

At the beginning, we set two default PLE values *LEAST_PLE* for 1.0 and *MOST_PLE* for 6.0 which in the sequence are the least value of PLE and the most value of PLE. And we start to calculate all T-R paths' PLEs, which are ple_1, ple_2, ..., ple_n, by following steps. First in T_1 to R_1 path, we set ple_1 as *LEAST_PLE* and count two distances by equation (8) with f_1, $S_{1,1}$ and f_2, $S_{1,2}$, then we can get two distances $d_{1,1}$ and $d_{1,2}$. Next we set the value *min* as $d_{1,1}$ minuses $d_{1,2}$ and ple_1 as ple_1 pluses 0.01, then we count two distances and get $d_{1,1}$ and $d_{1,2}$ again. We set *diff* as $d_{1,1}$ minuses $d_{1,2}$ like above and test whether *diff* is less than *min* or not. If *diff* is less than *min*, we set *min* as *diff*, ple_1 as ple_1 pluses 0.01, and count two distances, and do the action like above until *diff* is greater than *min* or ple_1 equals *MOST_PLE*. At last, we can get suitable PLE as ple_1 minuses 0.01 or *MOST_PLE* when ple_1 equals *MOST_PLE*. As the result, when there are n T-R paths, we have to do n PLE calibrations and get all ultimate values of ple_1, ple_2, ..., ple_n. These steps of PLE calibration are also showed in Figure 6.

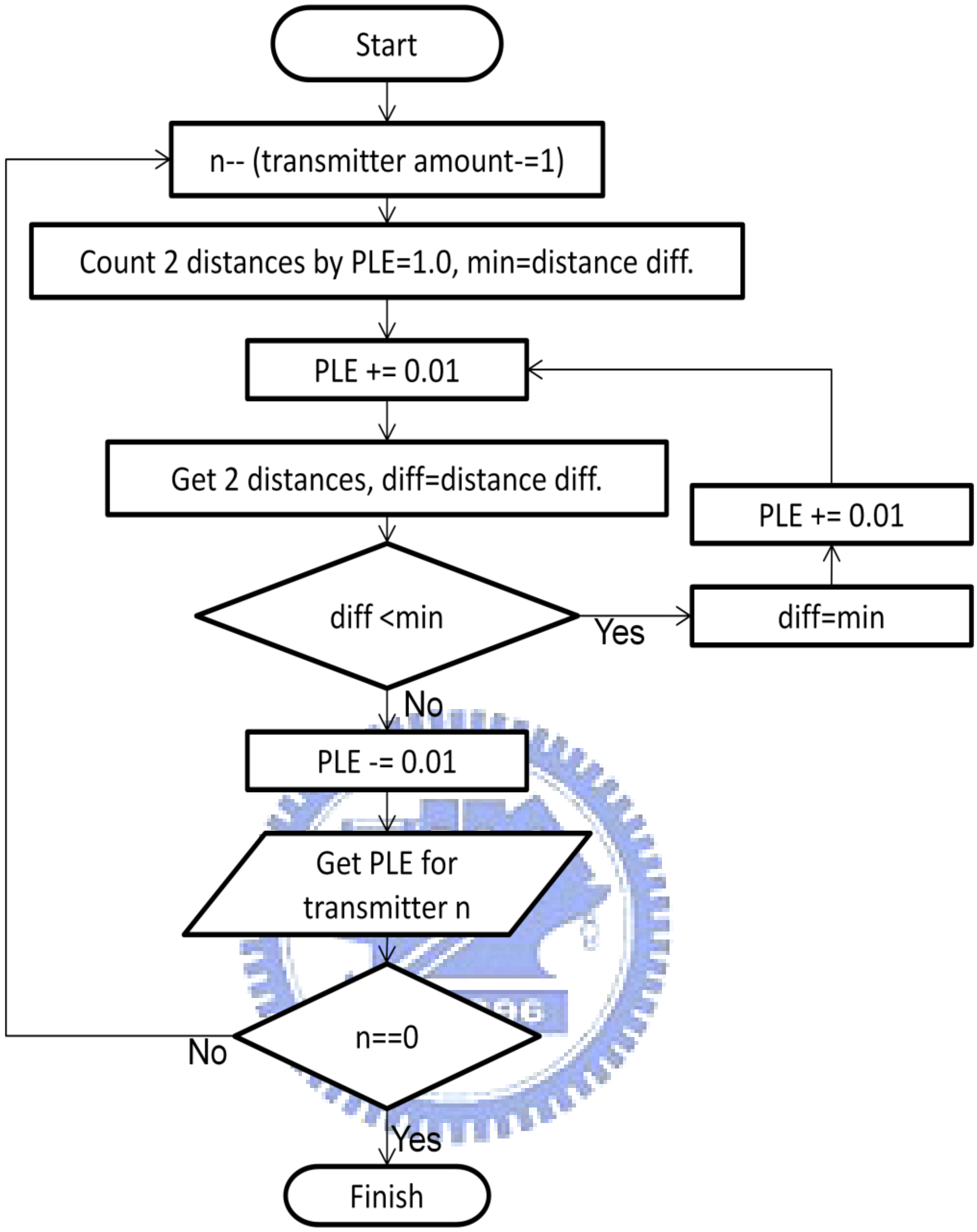

Figure 6: Steps of dynamic PLE calibration for each T-R path

The range of all PLEs in this step is from *LEAST_PLE* to *MOST_PLE*. However, few conditions show that PLE equals *LEAST_PLE* or *MOST_PLE* which means that the attenuation of signal strengths is very slow or very fast. Or on the other hand, one of two signals with different frequencies from the same transmitter through the same T-R path is confused so the attenuation rates of two signals may be large different with each other. For avoiding this problem, we will propose some methods for enhancing our positioning method in section 4.3 to solve it.

4.2.3 Check the Intersection Existence by Trilateration

In this step, we check that all T-R distances calculated by above PLE calibration can intersect an area with at least one position by trilateration. And after trilateration, if there is the intersection existing, we next iterate changing all PLEs of all T-R paths and calculating all T-R distances with new PLEs again for eliminating the intersection size to the smallest. Otherwise, if there is no intersection existing, we also repeatedly change all PLEs of all T-R paths and calculate all T-R distances with new PLEs until there is at least one position in the intersection by trilateration. The following is the steps of this stage.

At the beginning, we first calculate every T-R distance by equation (8) with above PLEs and their frequency f_1 and RSS $S_{i,1}$ of the transmitter i. And then we use every transmitter's position as the center and its estimated T-R distance to do trilateration for checking the existence of the intersection. After this step, if the intersection exists then we store all PLEs, take every PLE to add the value w which is counted by equation (12), calculate new T-R distance, and do trilateration. We repeat to do this step again and again until the intersection vanishes. And when the intersection vanishes, we restore forward PLEs and then go to the next step. On the other hand, if the intersection is not in the first check then we take every PLE to minus the value w which is also counted by equation (12), calculate new T-R distance, and do trilateration. We also do this step again and again until getting the intersection. And we go to the next step when the intersection appears, too. The flowchart of this section is shown in Figure 7.

$$w = \frac{w_i}{\sum_{k=1}^{n} w_k} \tag{12}$$

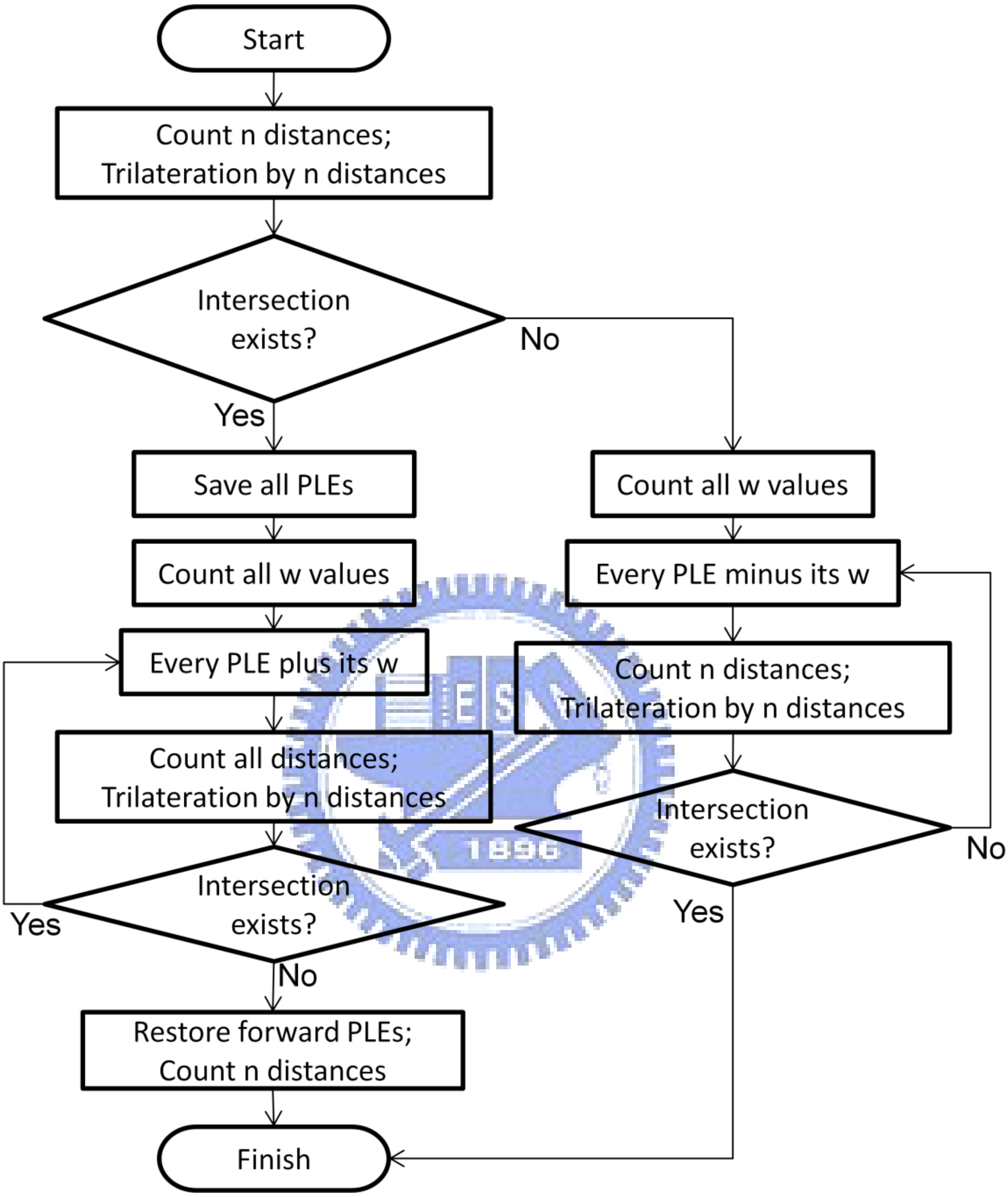

Figure 7: Steps of check the intersection existence by trilateration

4.2.4 Trilateration Positioning

By above steps, we can get all n T-R distances which are $d_{1,1}$, $d_{2,1}$, …, $d_{n,1}$ by equation (8) with their PLEs and RSSs of the signal with lower frequency f_1. And there is at least one point in the intersection from trilateration. The purpose what we want in this step is finding the best proper point in the intersection. And in section 2.3, we introduce the basic trilateration positioning method and its maximum likelihood method for finding the best point. We take this method for getting the point in this step, too. And after this method, the point what we get is the result of our robust trilateration positioning method.

However, some exceptions may be occurred in reality because of the fluctuation of the signal. For example, one of two signals with different frequencies through the same T-R path may be detrimentally changed hence we may estimate false PLE and calculate wrong distance of the T-R path. Moreover, the positioning result usually increases the error rate after the mistake. Therefore, in the next section we add and introduce three methods in our proposed scheme for reducing some special cases.

4.3 Special Cases Improvement

There are three special cases that we conclude in our proposed scheme. And followings are introductions of these three cases and their corresponding solutions in detail.

1. RSS with frequency f_1 signal is lower than frequency f_2 signal in step1.

   In general, RSS from the same transmitter with lower frequency must be greater than the higher one. However, few situations show that RSS with lower frequency is weaker than higher one. These situations may occur due to the fading effect or the specific absorption on some objects, random interferences through the T-R path, and etc. In our proposed scheme, this case may happen in step1 which is for measuring RSS. And if we get RSSs like that, we will eliminate this measurement and take this error transmitter out in next steps. But we must consider one condition that the amount of available transmitter is less than three after the action of the elimination. In this situation, we choose the transmitter which has the strongest RSS of the signal with frequency f_1 from those eliminated transmitters to achieve that at least three transmitters to do positioning.

2. Estimated PLE equals *LEAST_PLE* in step2.

   In step 2, the range of PLE what we calibrate is from *LEAST_PLE* (1.0) to *MOST_PLE* (6.0). And if PLE equals *LEAST_PLE* stands for that RSS from the signal with frequency f_1 attenuates fast than the signal with frequency f_2. Therefore, the T-R distance difference from these two RSSs is greater than the T-R distance difference calculated by PLE which is greater than *LEAST_PLE*. The method what we use to solve this problem is also eliminating error transmitters. But like case1, the available amount of transmitters may be less than three. In this situation, we also select the transmitter which has the strongest RSS of the signal with frequency f_1 from those eliminated transmitters to get at least three transmitters to do positioning.

3. Estimated PLE equals *MOST_PLE* in step2.

   In step 2, the value range which we estimate PLE is from *LEAST_PLE* (1.0) to *MOST_PLE* (6.0). And if PLE equals *MOST_PLE* stands for that RSS from the signal with frequency f_2 attenuates too fast than the normal attenuate rate of the signal with frequency f_1. Therefore, the T-R distance difference from these two RSSs continues narrowing when PLE of the distance difference calculation is from *LEAST_PLE* to *MOST_PLE*. The method what we use to solve this problem is also eliminating all error transmitters. But like above cases, available transmitters may be less than three. And we also choose the transmitter which has the strongest RSS of the signal with frequency f_1 from those eliminated transmitters to get at least three transmitters in this situation.

Chapter 5 Simulation Result

In this chapter, two simulation scenarios are held for verifying that the proposed method, robust trilateration positioning method, can get the accurate PLE for each T-R path and more precise position estimation than the traditional positioning method with static PLE. In the first section, we introduce our steps of the simulation which are constructing the environment, using the network simulator NS2 (version ns-2.33) [24] to simulate signal propagation and collect RSS information, doing the positioning by our proposed scheme, and evaluating the simulation results. And two simulations are performed in the next two sections. Finally in the last section, we evaluate the outcome between two simulations of our proposed scheme and the traditional method by comparing with their error rate.

5.1 Simulation Environment

The first step in our simulation is deciding all factors, which are the area size in the x-y coordinate, the amount of transmitters, and the to-be-estimated position (receiver), in the positioning space. And after the initial scenario is determined, we can use these settings to operate the network simulator tool, NS2, to generate RSSs between all transmitters and the to-be-estimated position. Finally, our robust trilateration positioning method uses those known environment data, positions of transmitters, and those RSSs to calculate all T-R distances with their own PLE and estimate the receiver's position.

The tool what we use for producing the RSS information for every T-R path in our simulation is NS2. And we first focus on its signal propagation models. There are three propagation models in NS2 which are free space model, two-ray ground reflection model, and shadowing model. And their corresponding equations are showed in equation (13), equation (14), and equation (15) where all variables are like propagation models what we introduce in section 2.2 but the variable L which is system loss and its default value is 1.0.

In our simulation, we use shadowing model for simulating signal propagation because of its PLE-changeable (*β*), and random-enable (X_{dB}). But being attention to equation (15), it counts RSS in dB unit but not in mW which is the power unit in NS2. Otherwise, $P_r(d_0)$ in shadowing model is the value calculated by free space model with the distance d_0 and PLE *β* which is 2 in fixed. However in our simulation, we want that most signals through different T-R paths have different attenuate rates. So we write new free space model which is equation (16) with value *β* for PLE which comes from shadowing model. As the result, all our $P_r(d_0)$ in shadowing model are counted by this new model. All values of important variable in NS2 shadowing model what we set are showed in Table 3. Moreover, all antenna gains (G_t and G_r) are set as 1.0 because they are not the consideration in our simulation.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (13)$$

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \quad (14)$$

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \quad (15)$$

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^\beta}{(4\pi)^\beta {d_0}^\beta L} \quad (16)$$

Table 3: Variables of shadowing model in NS2

Variable setting name	**Simulation value**
pathlossExp_	Changed by every T-R path
std_db_	10.0
dist0_	1.0

Two different frequencies what we use for the transmitter to send signals are 914MHz and 2.4GHz. We use these two frequencies because they are common used spectrums and also used by a lot of wireless devices. On the other hand, in the respect of our simulation,

Table 4 lists all variables of the environment for our simulation scenario.

Table 4: Variables of simulation scenario

Environmental variables
Area size (meter^2)
Transmitter amount
Transmitted power (mW)
PLE for each T-R path (from 2.0 to 5.0)
Coordinate accuracy unit (meter)
Estimation position (Receiver) amount
Estimation times for one position

After simulation of NS2 produces all RSS information, we can gather these RSS information and do next simulations in our desktop with our robust trilateration positioning method and the traditional trilateration positioning method to estimate the position. The equipments of our desktop for doing these all simulations are showed in Table 5. And finally after all simulations, we take the position error as the criterion for evaluating our robust trilateration positioning method with traditional trilateration positioning method.

Table 5: Computer equipments for running simulation

Device	**Equipment**
CPU	Intel Core 2 CPU 440 @ 2.00GHz
RAM	2.0 G
Operating system	Ubuntu 2.6.27-7-server
Programming language / Compiler	C++ / g++ 4.3.2

5.2 Simulation-1

The simulation-1 is for simulating the positioning space in the indoor room. This space size is 8 meter by 8 meter. The transmitter amount is from 4 to 8. The estimated position amount is 9. And each transmitted power is set as 1.0mW. Above variables and others are also arranged in Table 6. On the other hand, all T-R paths' PLE, which are generated by the random number from 2.0 to 5.0, are showed in Table 7. Otherwise, this scenario is also described in Figure 8, and Table 8 shows all nodes' corresponding numbers.

Table 6: Environmental variables in simulation-1

Environmental variables	**Value**
Area size	8 x 8 m^2
Transmitter amount	4 ~ 8
Transmitted power	1.0 mW
PLE for each T-R path	2.0 ~ 5.0
Coordinate accuracy unit	0.1 m
Estimation position (Receiver) amount	9
Estimation times of one position	100

Table 7: PLEs in simulation-1 for NS2 to generate RSS information

	T1	T2	T3	T4	T5	T6	T7	T8
Pos1	2.41	2.27	2.89	2.27	2.77	2.91	3.3	4.33
Pos 2	4.54	3.73	2.97	4.04	3.41	2.93	3.47	2.67
Pos 3	4.27	2.02	3.38	2.71	3.66	3.07	2.12	2.59
Pos 4	3.03	4.6	2.1	2.21	2.47	3.42	4.63	2.89
Pos 5	3.69	2.51	3.16	4.46	3.42	4.46	3.78	2.96
Pos 6	3.2	4.75	2	4.61	2.68	3.48	2.28	4.94
Pos 7	3.49	3.66	2.65	2.16	4.73	2.77	2.75	2.75
Pos 8	2.36	2.85	2.96	2.84	4.27	2.59	3.73	2.96
Pos 9	3.11	4.89	2.42	4.53	4.35	4.2	2.49	2.55

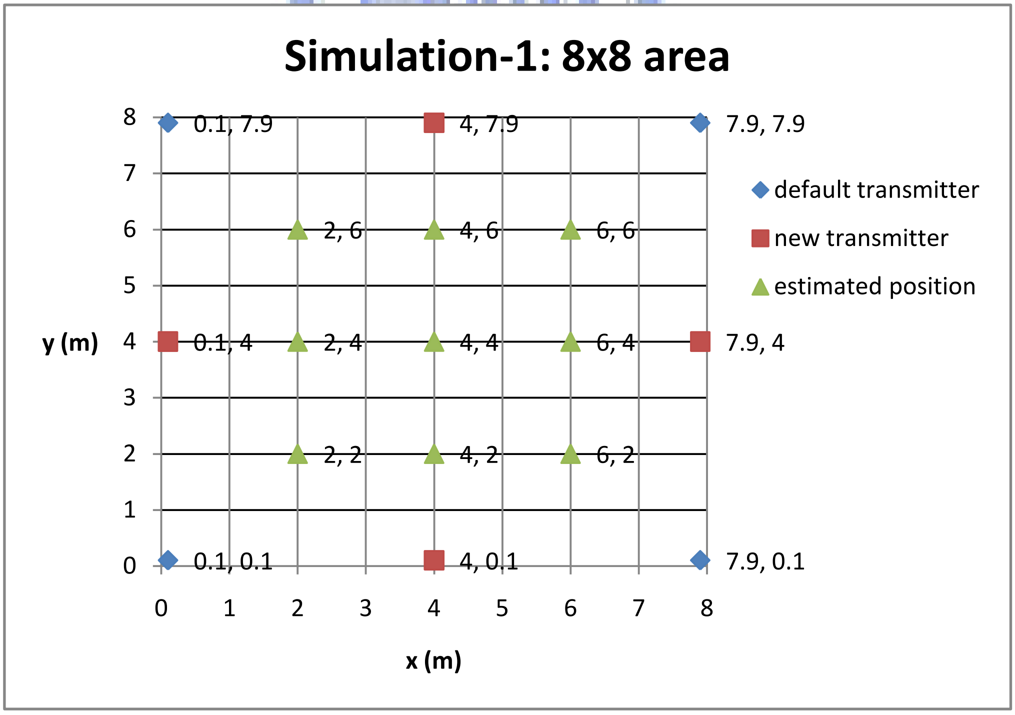

Figure 8: Simulation-1 scenario

Table 8: Transmitter no. and estimated receiver position no. in simulation-1

Transmitter	1	2	3	4	5	6	7	8	
Position	(0.1,0.1)	(7.9,0.1)	(0.1,7.9)	(7.9,7.9)	(4,0.1)	(4,7.9)	(0.1,4)	(7.9,4)	
Receiver	1	2	3	4	5	6	7	8	9
Position	(2,2)	(4,2)	(6,2)	(6,4)	(4,4)	(2,4)	(2,6)	(4,6)	(6,6)

After this simulation, we can get Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13 which are results of positioning estimations in the space by 4 to 8 transmitters and each node of results is the mean value of 10 times' estimations. Moreover, Figure 14 shows all transmitters' comparison. Otherwise, we will discuss the estimation error rate and its result in section 5.3.

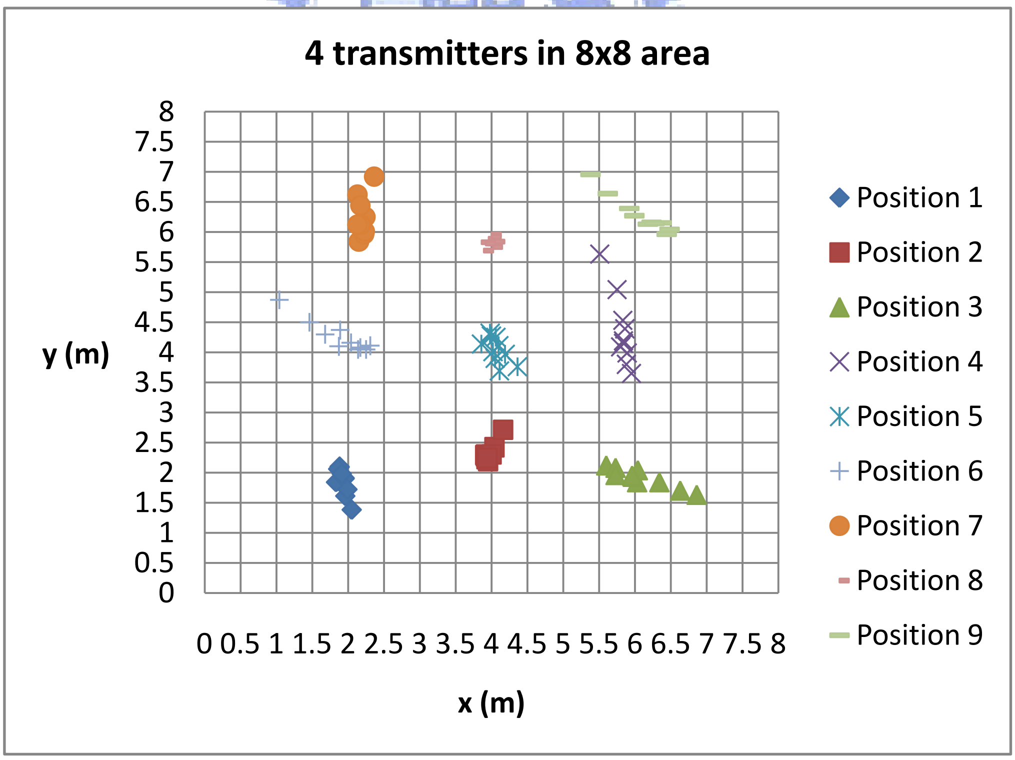

Figure 9: Positioning results of 4 transmitters in simulation-1

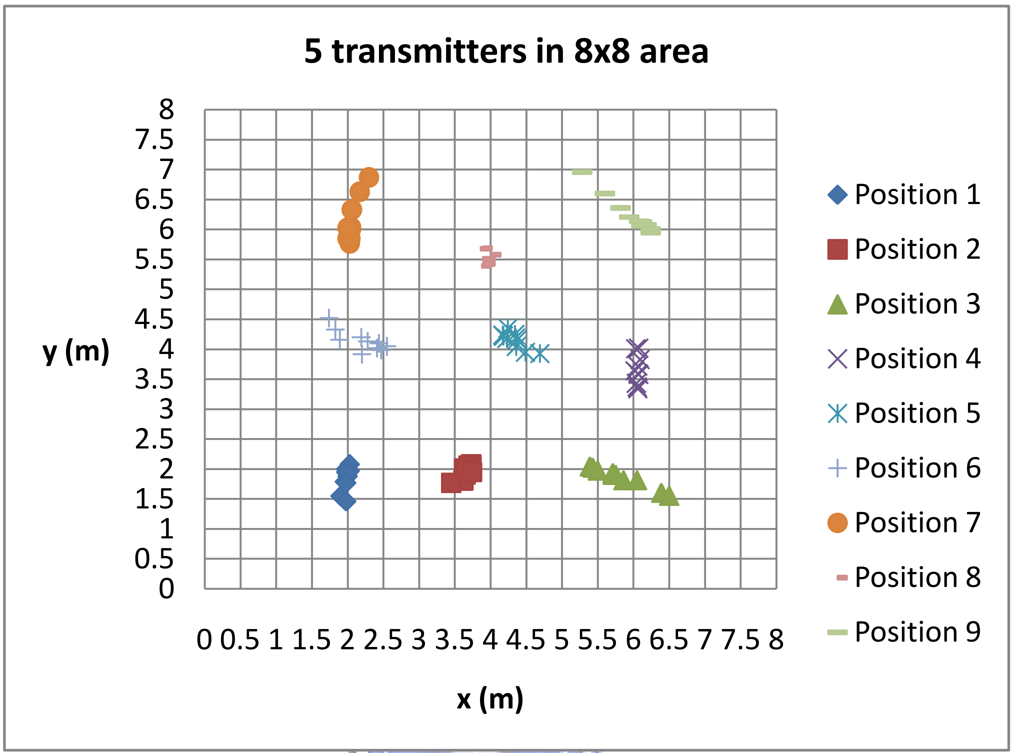

Figure 10: Positioning results of 5 transmitters in simulation-1

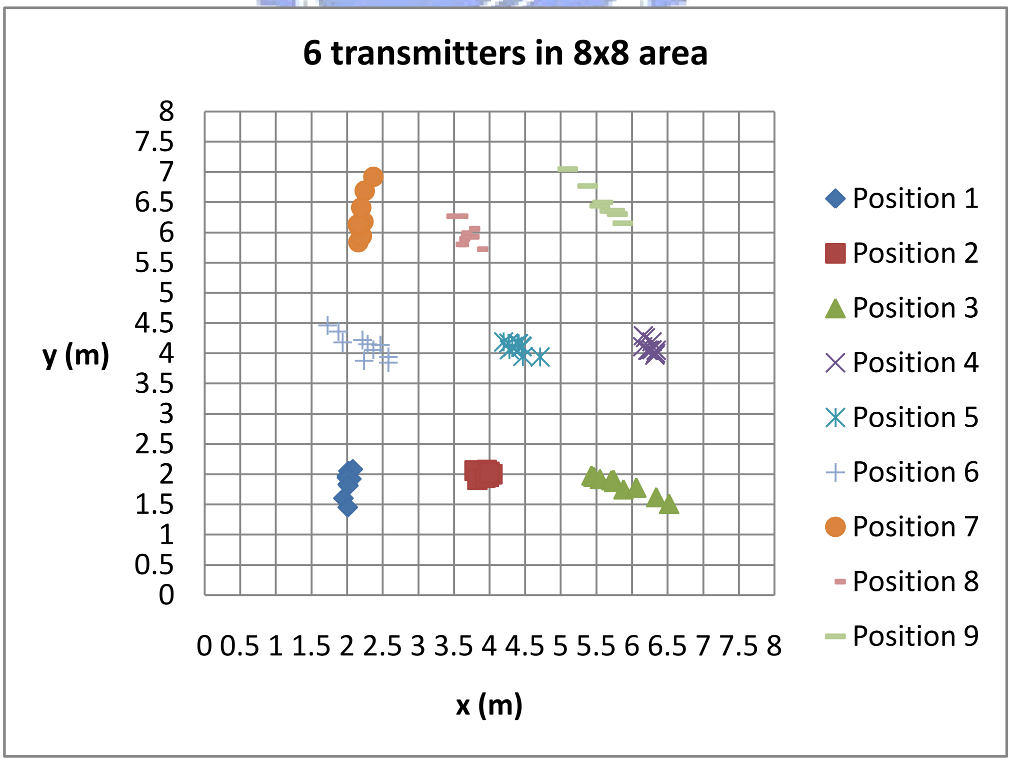

Figure 11: Positioning results of 6 transmitters in simulation-1

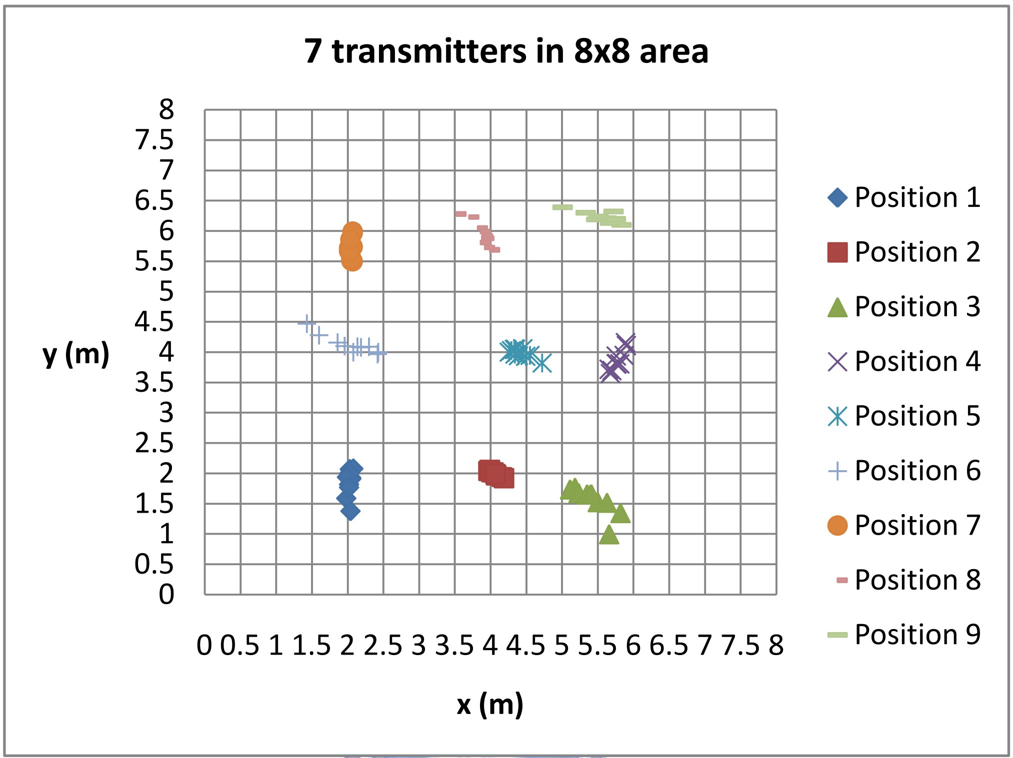

Figure 12: Positioning results of 7 transmitters in simulation-1

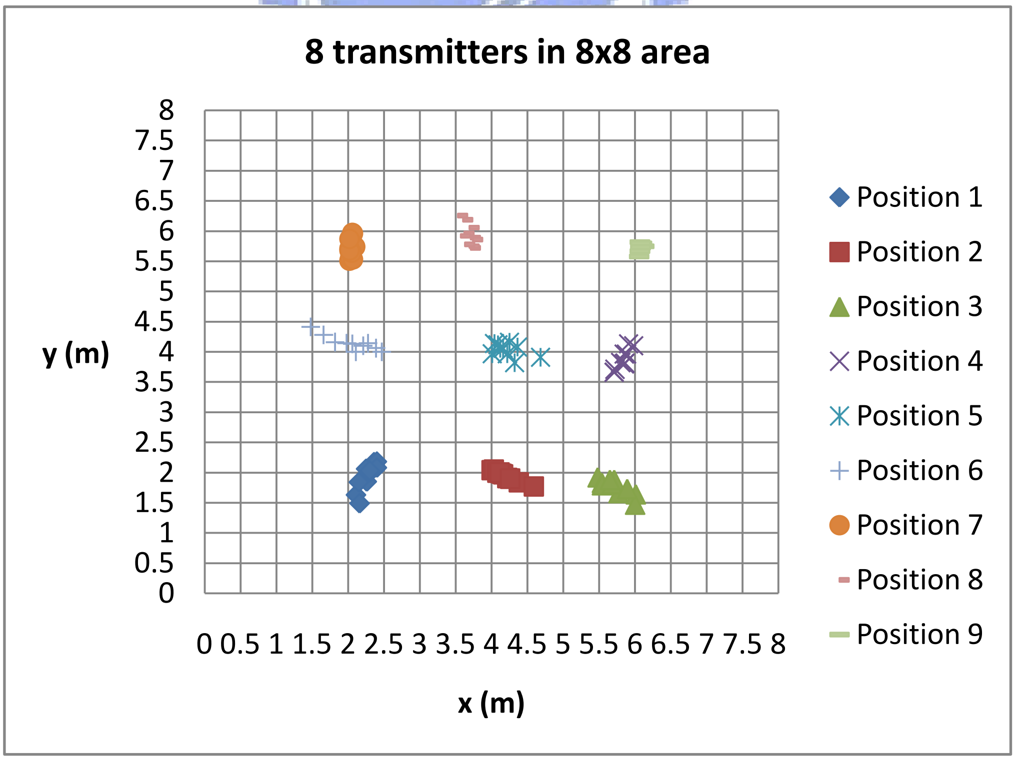

Figure 13: Positioning results of 8 transmitters in simulation-1

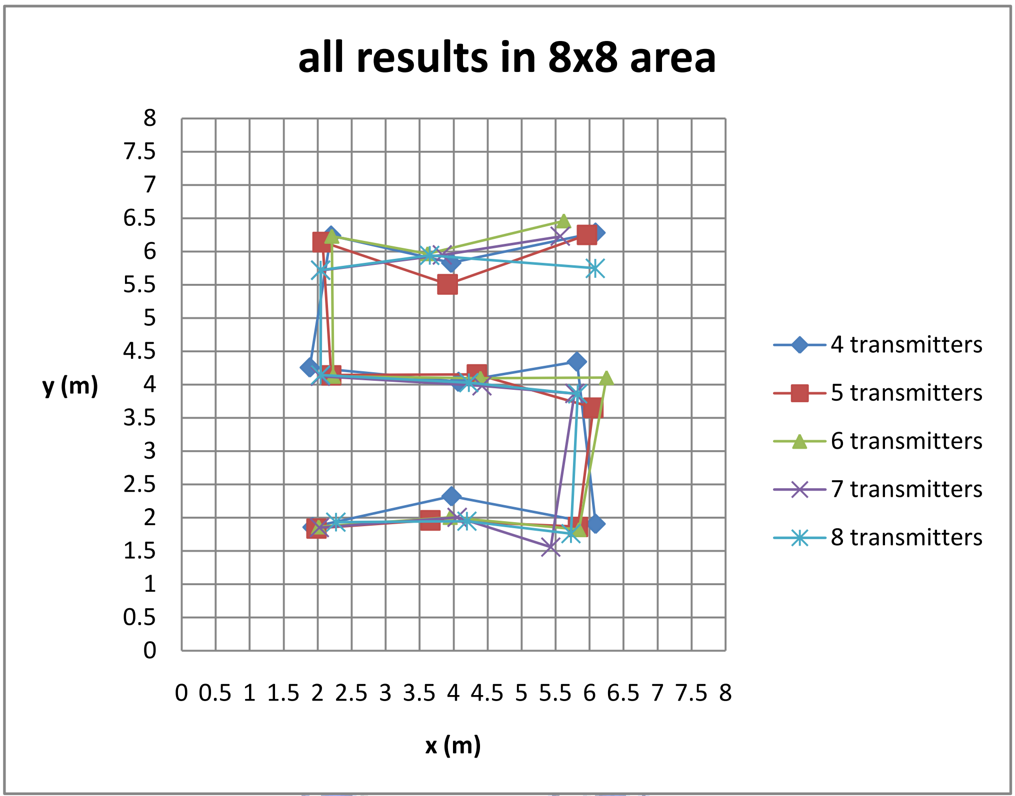

Figure 14: Positioning results of all transmitter amounts in simulation-1

5.3 Simulation-2

The simulation-2 is for simulating the positioning space of the indoor floor. This space size is 60 meter by 60 meter. The transmitter amount is from 8 to 13. The estimated position amount is 16. And each transmitted power is set as 10.0mW. Above variables are also arranged in Table 9. On the other hand, all T-R paths' PLE are showed in Table 10 which is generated by the random number from 2.0 to 5.0. Otherwise, the scenario is also described in Figure 15, and Table 11 shows all nodes' corresponding numbers.

Table 9: Environmental variables in simulation-2

Environmental variables	**Value**
Area size	60 x 60 m^2
Transmitter amount	8 ~ 13
Transmitted power	10.0 mW
PLE for each T-R path	2.0 ~ 5.0
Coordinate accuracy unit	0.5 m
Estimation position (Receiver) amount	16
Estimation times of one position	100

Table 10: PLEs in simulation-2 for NS2 to generate RSS information

	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**
Pos1	3.95	2.49	2.15	4.63	3.97	2.43	4.57	2.46	4.09	2.22	2.61	3.82	2.99
Pos2	3.36	4.57	3.36	4.21	2.54	4.19	3.48	3.13	2.92	4.44	4.24	2.81	4.86
Pos3	3.76	2.16	4.06	4.25	2.7	3.01	4.74	2.86	2.64	3.71	3.29	2.22	4.16
Pos4	2.38	2.44	4.78	4.2	3.43	3.13	3.77	4.78	2.34	4.31	3.98	3.82	2.44
Pos5	4.9	3.26	4.68	2.71	3.12	3.44	2.86	2.18	2.69	3.57	3.19	2.43	4.43
Pos6	3.83	4.13	2.71	4.05	3.29	3.1	4.49	3.07	2.3	2.92	4.2	4.07	2.7
Pos7	4.55	3.38	4.68	3.37	3.82	4.58	4.62	3.49	2.28	2.74	4.93	3.15	2.92
Pos8	2.62	4.72	4.1	3.05	4.14	2.93	2.18	4.86	4.98	3.47	2.95	4.47	4.54
Pos9	3.25	2.38	3.74	2.32	3.08	3.29	3.7	2.76	4.66	2.52	2.34	4.28	4.01
Pos10	2.63	2.02	3.94	3.78	2.94	4.56	3.49	2.04	2.61	2.63	2.97	2.79	2.49
Pos11	2.95	4.26	3.44	2.42	3.8	4.69	2.8	2.54	2.01	3.89	3.83	3.7	4.65
Pos12	3.49	4.22	4.99	2.77	3.23	2.62	2.79	2.17	4.4	3.72	4.73	2.89	3.76
Pos13	2.34	3.52	4.73	3.12	4.01	2.69	2.38	2.46	3.11	4.18	2.15	3.91	4.72
Pos14	2.15	2.8	3.55	3.85	2.45	2.04	3.07	2.45	2.81	4.29	3.07	3.6	4.46
Pos15	2.47	2.32	4.19	3.36	4.08	4.53	4.88	3.82	2.65	3.9	4.51	3.03	4.35
Pos16	2.62	2.2	4.5	4.53	4.92	4.65	2.33	3.47	3.5	2.78	3.51	4.57	3.23

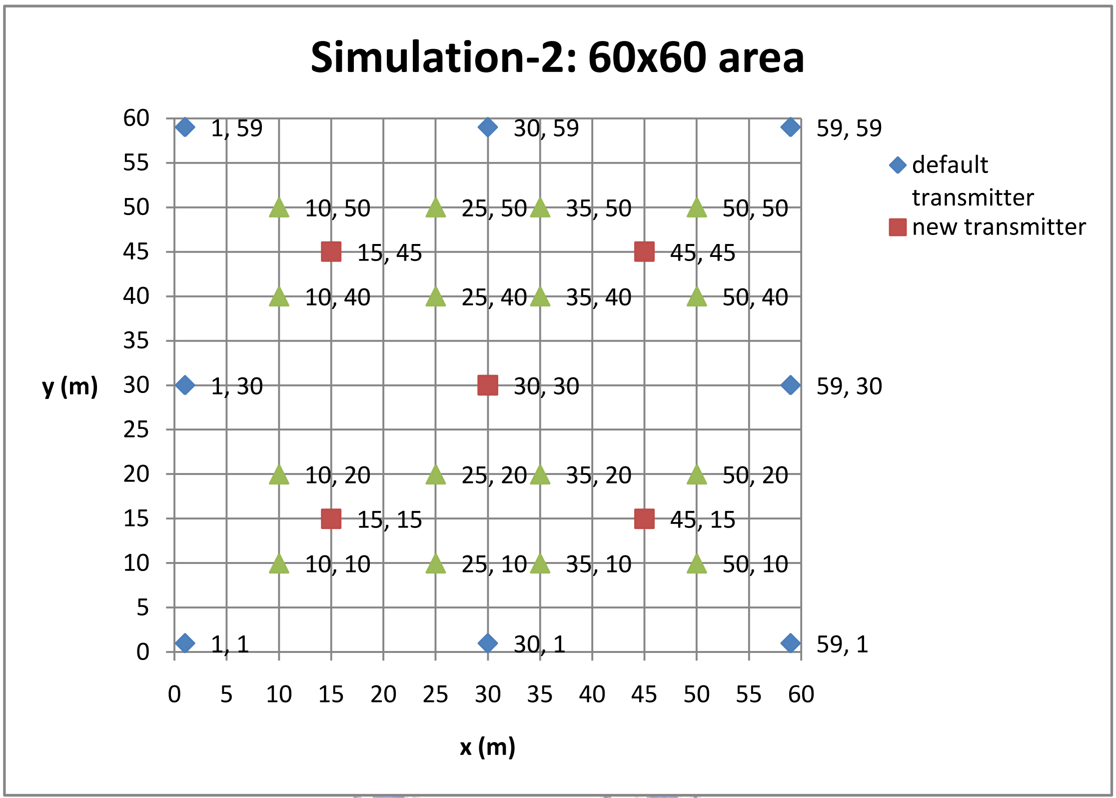

Figure 15: Simulation-2 scenario

Table 11: Transmitter no. and estimated receiver position no. in simulation-2

Transmitter	1	2	3	4	5	6	7	8
Position	(1,1)	(30,1)	(59,1)	(1,30)	(59,30)	(1,59)	(30,59)	(59,59)
Transmitter	9	10	11	12	13			
Position	(30,30)	(15,15)	(45,45)	(45,15)	(15,45)			
Receiver	1	2	3	4	5	6	7	8
Position	(10,10)	(25,10)	(35,10)	(50,10)	(50,20)	(35,20)	(25,20)	(10,20)
Receiver	9	10	11	12	13	14	15	16
Position	(10,40)	(25,40)	(35,40)	(50,40)	(50,50)	(35,50)	(25,50)	(10,50)

After the simulation, we can get Figure 16, Figure 17, Figure 18, Figure 19, Figure 20, and Figure 21 which are results of positioning estimation in the space by 8 to 13 transmitters and each node of results is the mean value of 10 times' estimations. Moreover, Figure 22 shows all transmitters' comparison. Otherwise, we will discuss the estimation error rate and its result in section 5.3.

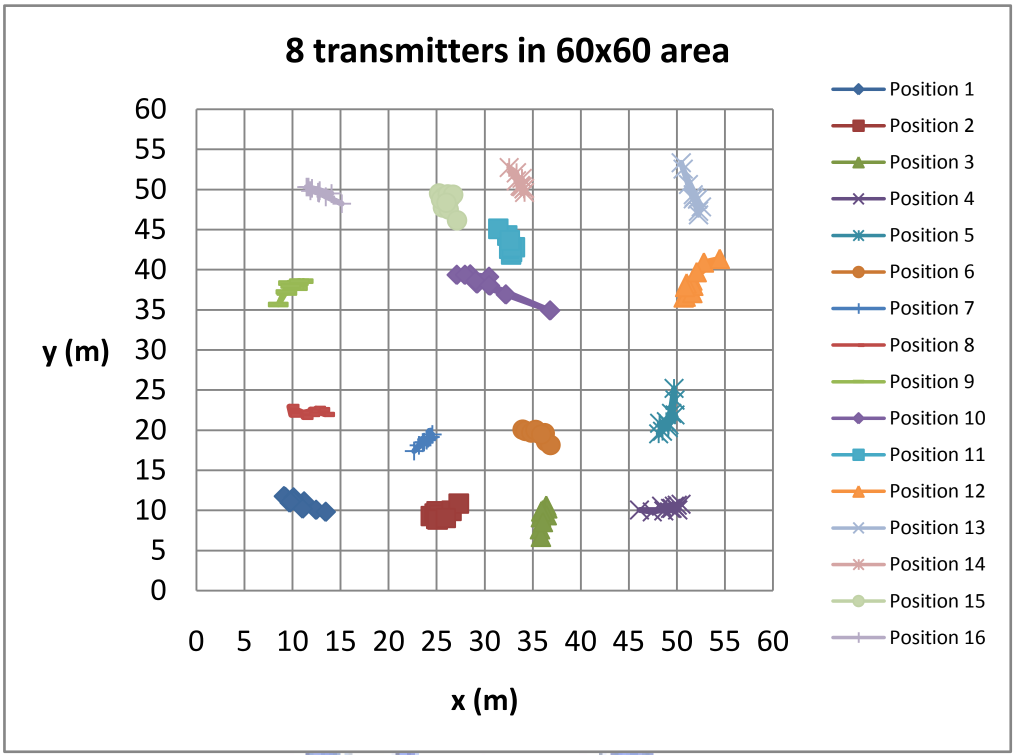

Figure 16: Positioning results of 8 transmitters in simulation-2

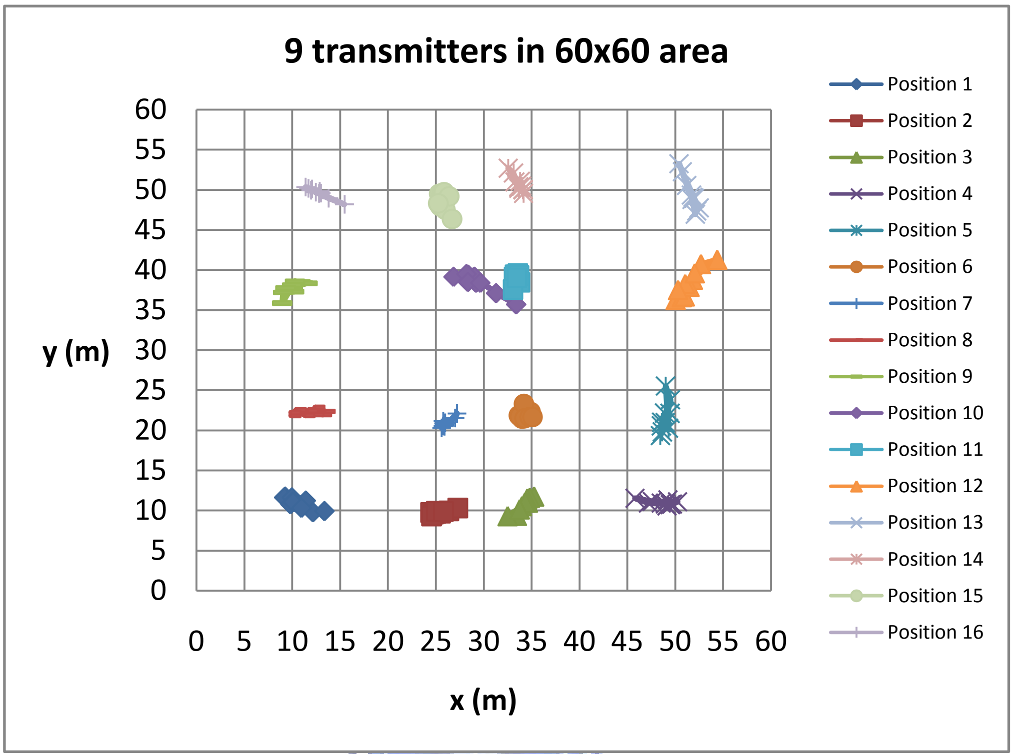

Figure 17: Positioning results of 9 transmitters in simulation-2

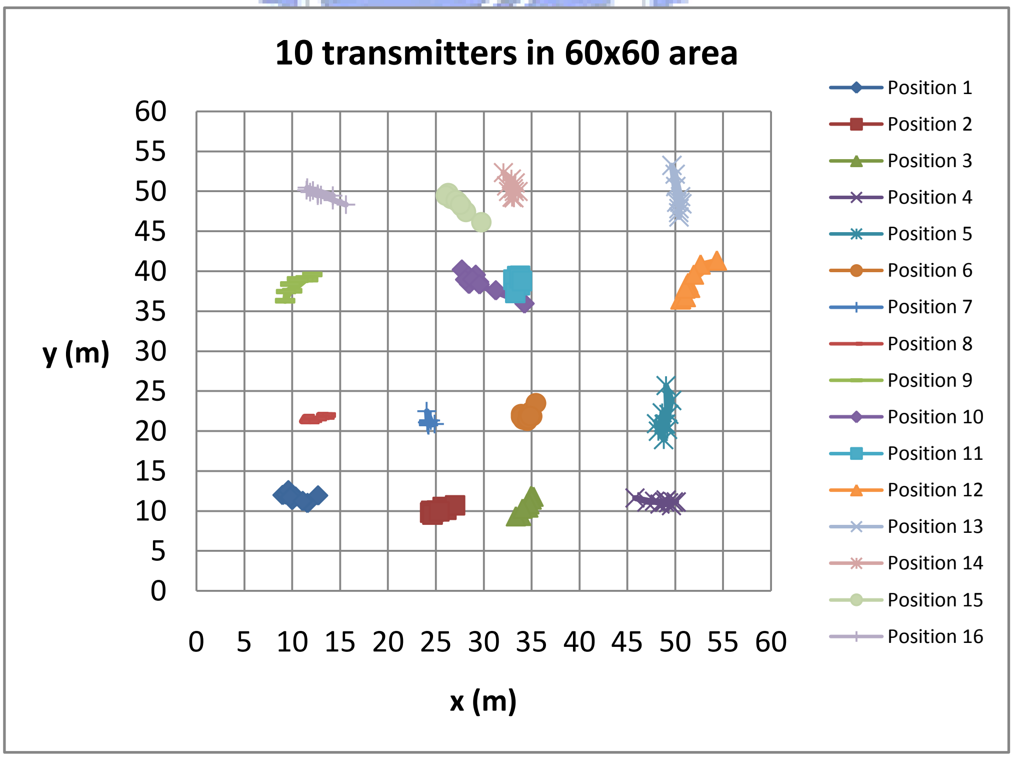

Figure 18: Positioning results of 10 transmitters in simulation-2

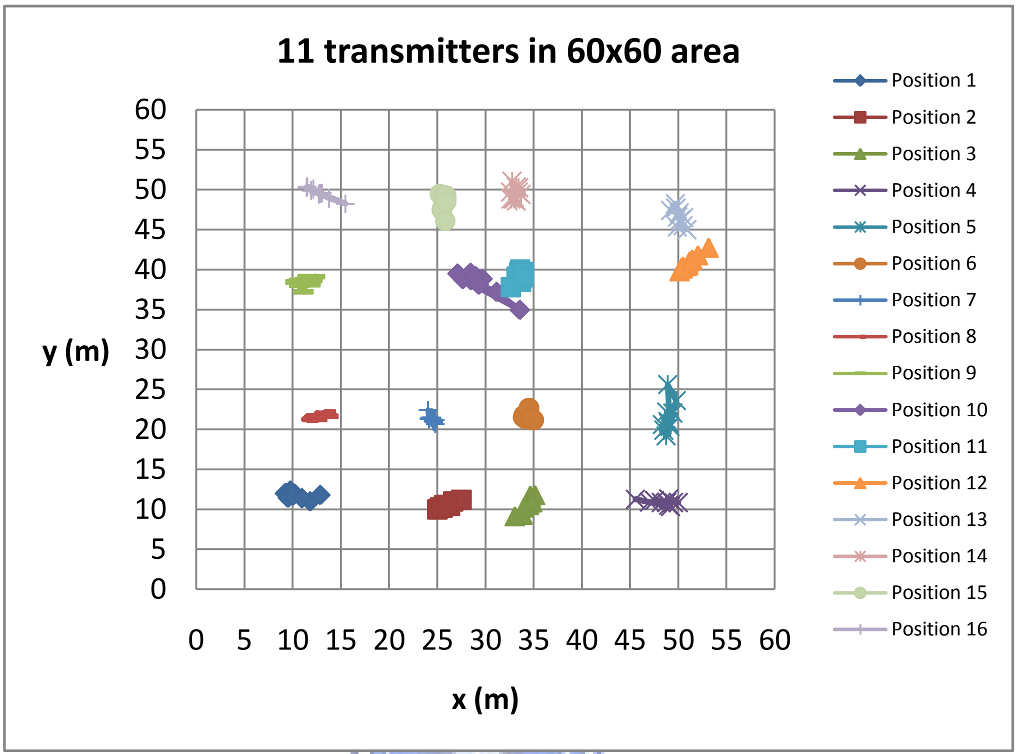

Figure 19: Positioning results of 11 transmitters in simulation-2

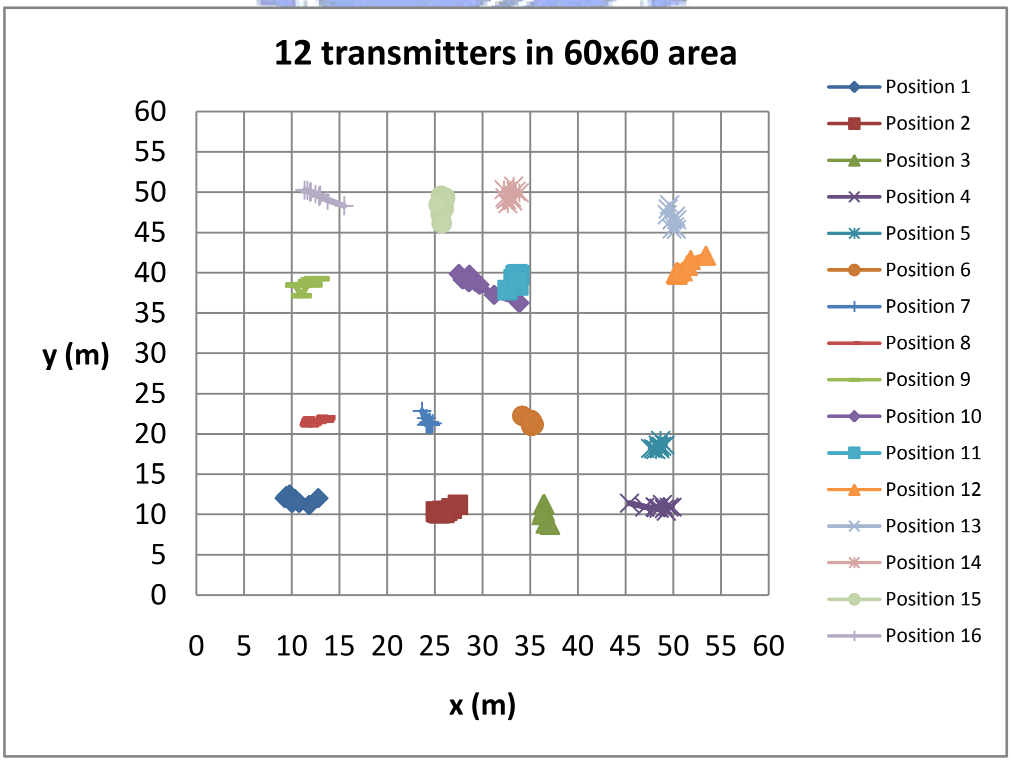

Figure 20: Positioning results of 12 transmitters in simulation-2

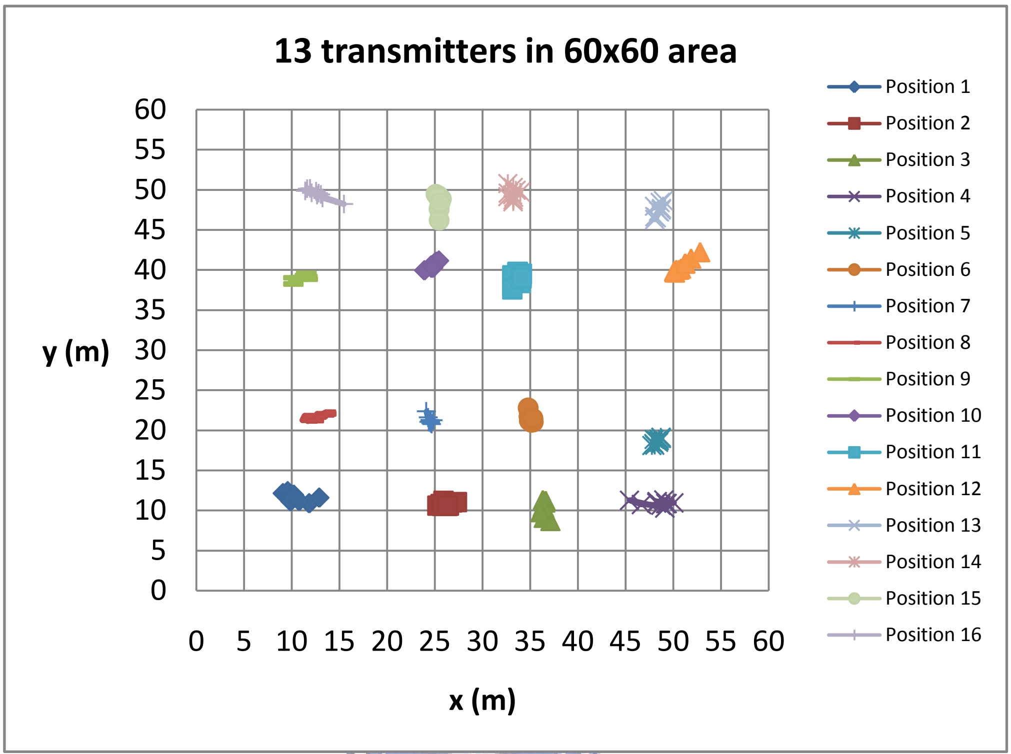

Figure 21: Positioning results of 13 transmitters in simulation-2

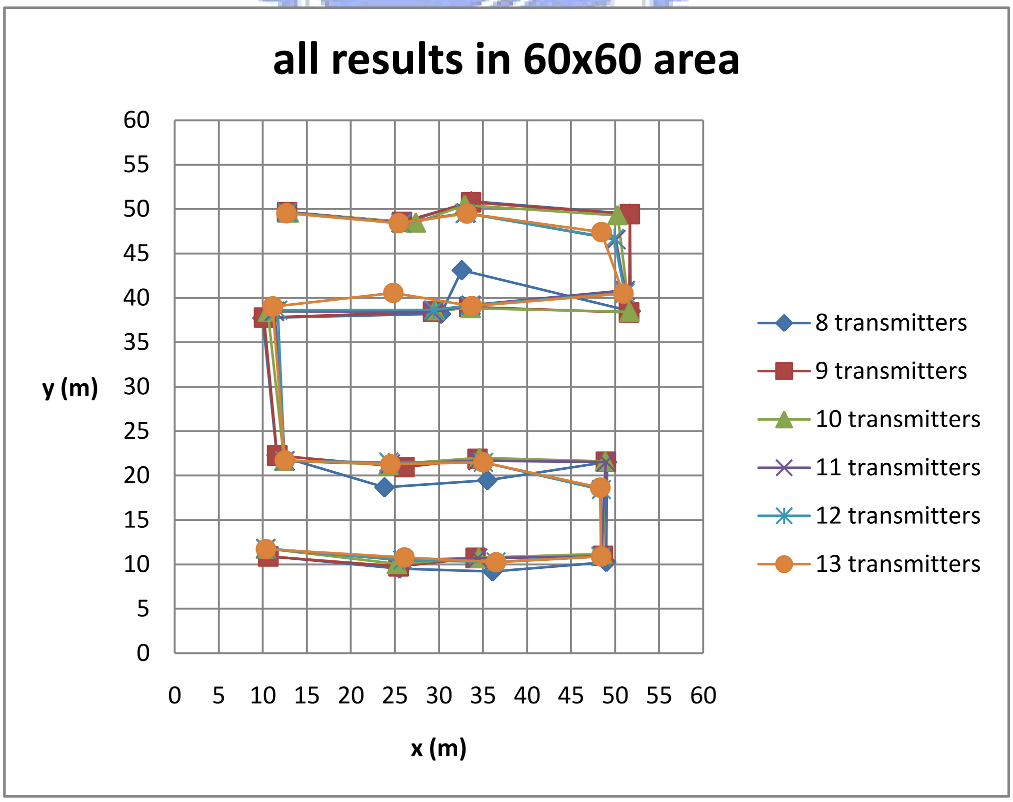

Figure 22: Positioning results of all transmitter amounts in simulation-2

5.4 Evaluation

In this section, we first evaluate the simulation result by the mean of position errors in simulation-1. When we look at all positioning results with different amounts of transmitters, we can find that positioning results are more precise and all estimated positions gather closer to each other when increasing transmitters. Moreover, Figure 14 shows the comparison of all results of all amounts of transmitters, and we clearly find that the positioning accuracy increases with the amount of transmitters increase.

Next we take the simulation result into the numeric comparison in Figure 23 which is the amount of transmitters versus mean errors of estimated positions. We first can see that all mean errors are less than 1.5 meter. And being attention on the performance of 4 transmitters to the performance of 8 transmitters, we can find that the mean error of 8 transmitters is really better than the mean error of 4 transmitters. But on the other hand, we also can see that positioning mean errors look a little disorder on different positions. This phenomenon is generated due to huge deviation on PLEs of some T-R paths at one positioning step. For example, the positioning result with 4 transmitters in position no.6 performs the big mean error because their PLEs are 3.2, 4.75, 2, and 4.61. Moreover, the positioning result with 4 transmitters in position no.8 performs the smaller mean error than increasing the amount of transmitters. By checking PLEs in this situation, we can find that transmitter no.5 causes the disorder on PLEs so the mean error increases. We can also obtain this information clearly after comparing Table 7 and Figure 23.

Finally in Figure 24, it is easy to find that the result is that the mean errors decrease when the amount of transmitters increases. And although the positioning result with 4 transmitters is worse than others, its mean error is still less than 1 meter.

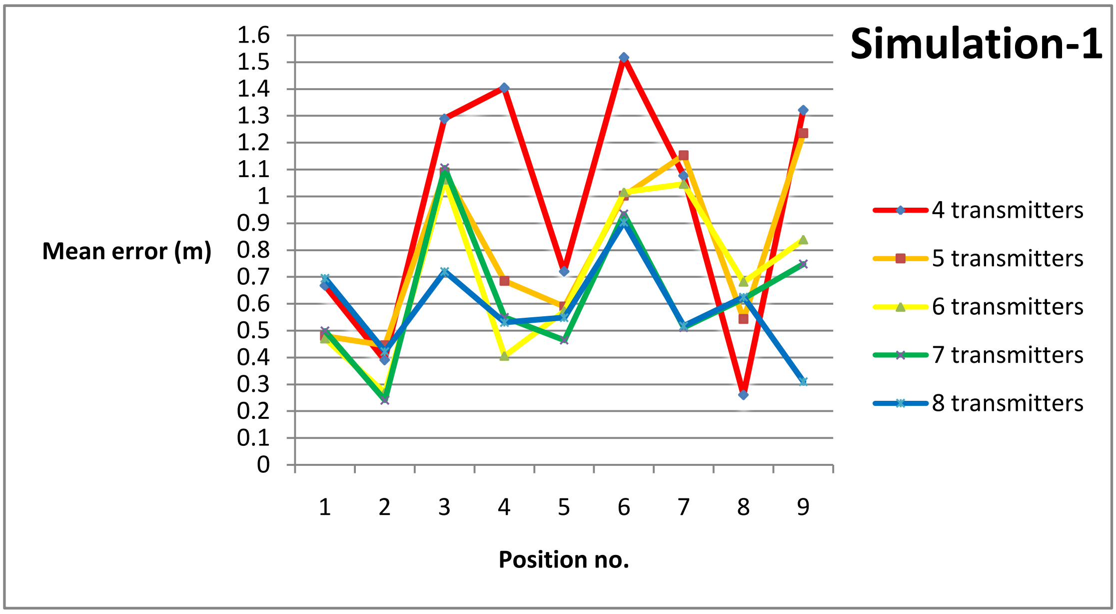

Figure 23: Positioning mean error with each position of 4 to 8 transmitters in simulation-1

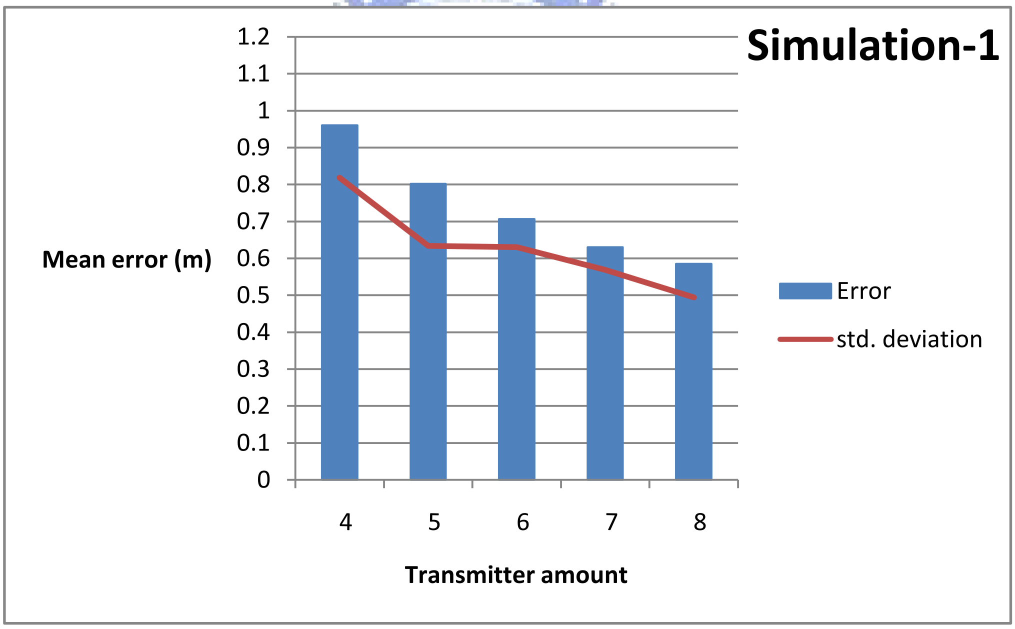

Figure 24: Positioning mean error with transmitter amount in simulation-1

In simulation-2, first when we look at all positioning results with different amounts of transmitters, we can find that increasing transmitters lets the positioning results be closer to its real position like simulation-1. And all estimated positions also gather closer to each other. Moreover, Figure 22 shows the comparison of all results of all amounts of transmitters. And we can also see that the positioning accuracy is increased with the amount of transmitters is increased like simulation-1.

Otherwise, we also take the simulation result into the numeric comparison in Figure 25 which is the amount of transmitters versus mean errors of estimated positions. We find that all mean errors are less than 7 meter. And being attention on the performance of 8 transmitters to the performance of 13 transmitters, we get that the mean error of 13 transmitters is really better than the mean error of 8 transmitters. However, it can be found that positioning mean errors look disorder, too. The reason of this phenomenon is like simulation-1. And we can also obtain this information clearly after comparing Table 10 and Figure 25.

In Figure 26, it is easy to find that the result is that the mean errors decrease when the amount of transmitters increases. And although the positioning result with 8 transmitters is worse than others, its mean error is still less than about 4 meter.

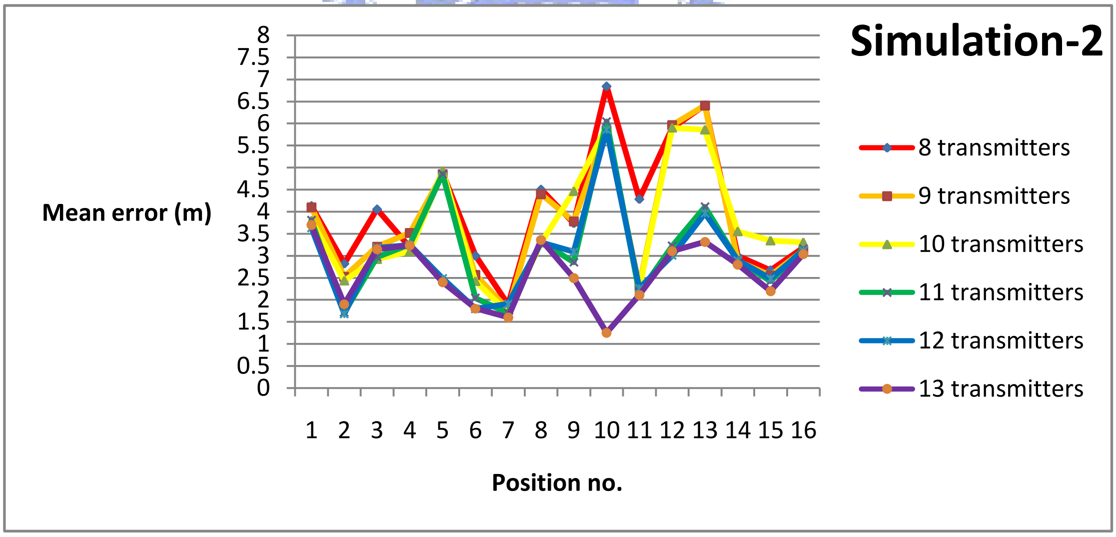

Figure 25: Positioning mean error with each position of 8 to 13 transmitters in simulation-2

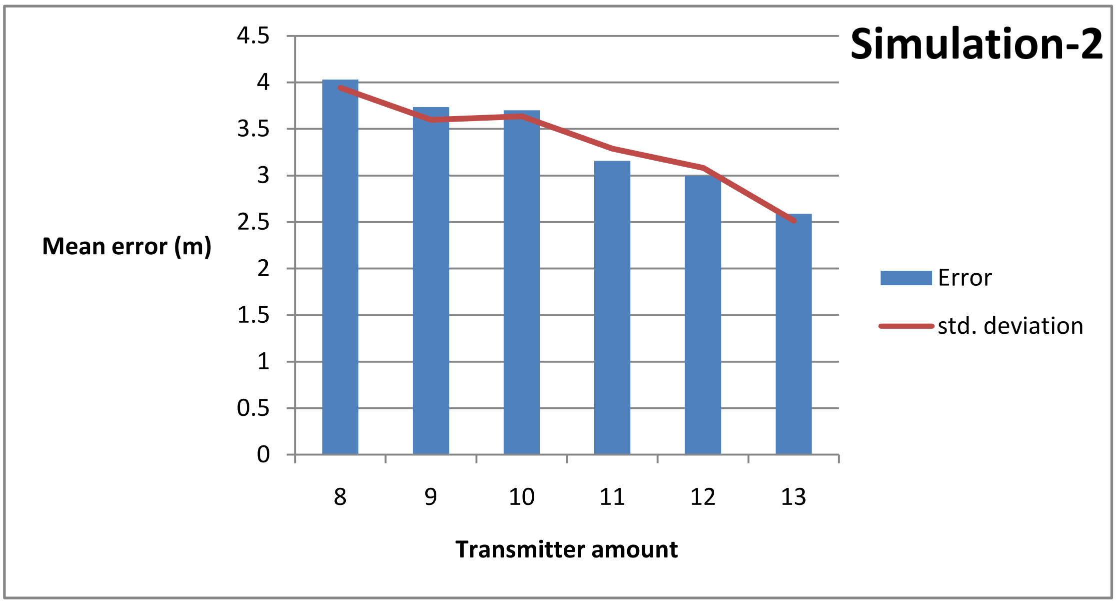

Figure 26: Positioning mean error with transmitter amount in simulation-2

Furthermore, we can find that the mean error of simulation-1 is less than simulation-2. In this issue, we need to consider one condition which is the node degree with the space size. In simulation-1, there are 4 to 8 transmitters on the area of 8 meter by 8 meter. But in simulation-2, there are 8 to 13 transmitters on the area of 60 meter by 60 meter. So when the density of transmitters is referenced, the mean error of simulation-1 is indeed less than simulation-2.

Otherwise, for proving our proposed scheme has better performance in the real space which is the PLE-changeable environment. We do simulation-1 again with setting all T-R paths' PLE as 3.0 in step2 of our robust trilateration positioning method for calculating T-R distances. After this new simulation, we get the result of the positioning mean error which is showed in Figure 27. We can find that the result shows high mean errors from about 3.3 meter to 2.1 meter. So by comparing this simulation with above simulation-1, we can verify that our proposed scheme has more accuracy positioning in the PLE-changeable environment.

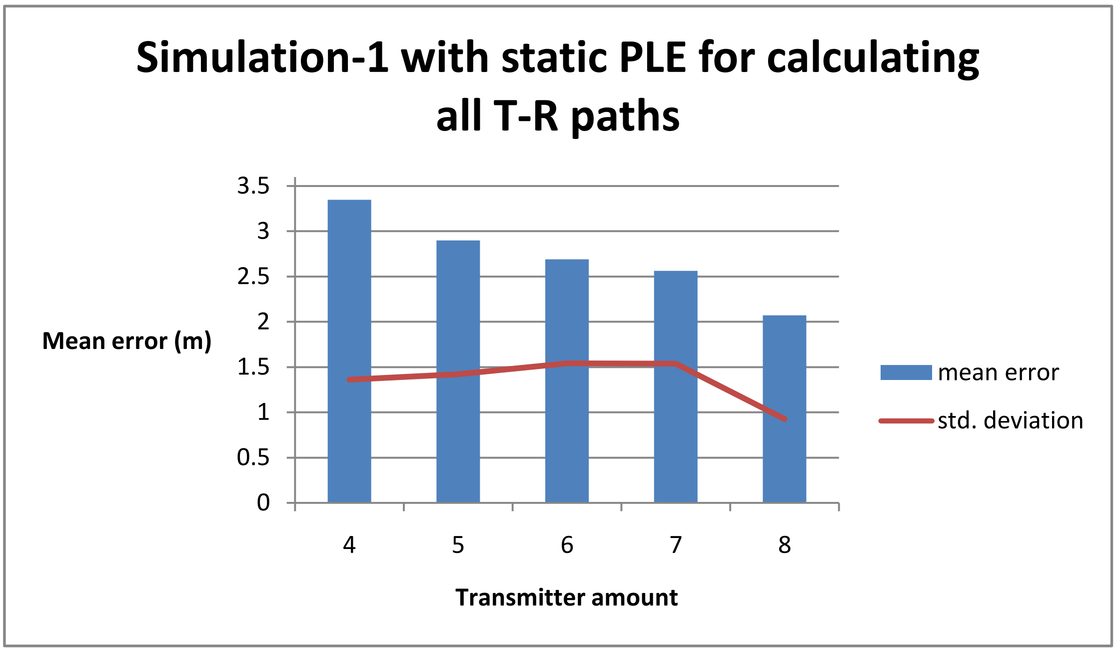

Figure 27: Positioning mean error with transmitter amount in simulation-1 with static PLE

Chapter 6 Conclusion

6.1 Conclusion

In the radio propagation, when the transmitter emits the signal to the receiver in the space, we can find that all different propagation paths have their own signal strength attenuate rates which we call path loss exponent (PLE). On the other hand, if we calculate the distance by the RSS-to-distance equation with right PLE on the T-R path, we can get the more accurate distance estimation. And in the RSS-based positioning system which uses the relationship between the T-R distance and RSS to do positioning, if most estimated T-R distances are more precise, we can get the more precise positioning result.

In this thesis, we propose the method to calibrate all PLEs for all T-R paths by two signals with two different frequencies in the RSS-based positioning system. Therefore, we can use these estimated PLEs to calculate all T-R distances and do positioning by trilateration with these estimated distances. The method what we propose is called robust trilateration positioning method. And by using our method in simulations, we can get the result that the accuracy of the positioning result is more precise than the traditional positioning method with static PLE. In our simulation of the indoor room which is 8 meter by 8 meter, it shows that the mean error is in 0.5 meter to 1 meter. This result of simulation-1 is better than the simulation with the same conditions but static PLE for calculating all T-R distances. The simulation with static PLE calculation shows that the mean error is in 2.1 meter to 3.3 meter. Furthermore in simulation-2 of the indoor floor which is 60 meter by 60 meter, the result shows that the mean error is in 2.5 meter to 4 meter due to its lower node density compared to simulation-1.

6.2 Future Work

Our proposed scheme in this thesis is using two signals with two different frequencies to do positioning. And in our simulation we just use frequency spectrums in 914MHz and 2.4GHz. However, if one of two signals is destroyed by its specific characteristics of the signal, PLE, the estimated distance, and the positioning result all may be huge false. So in the future work, we think that if more signals with more different frequencies are used, we may avoid some impacts or mistakes by comparing with many signals. And we can also do some actions like eliminating wrong signals or tuning the information of the signal for calibrating more precise PLE or calculating the more accurate T-R distance.

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