RFID-BASED LOCATION TRACKING SYSTEM

USING A PEER-TO-PEER NETWORK ARCHITECTURE

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RFID-based Location Tracking System Using a Peer-to-Peer Network Architecture

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CERTIFICATE OF ORIGINALITY

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Abstract

In recent years, the Global Positioning System (GPS) has been commonly employed for outdoor positioning and location tracking. On the other hand, there has also been growing interest in developing indoor location tracking systems. Advancements in radio frequency identification (RFID) technology make it a promising technology for use in indoor location tracking systems. While RFID technology has been designed for identification purposes, it can also be used for location tracking purposes. In this research, we present an RFID-based location tracking system using a peer-to-peer (P2P) network architecture and investigate location estimation methods for the system, which can provide flexibility for system implementation and cost-effectiveness for system maintenance. The proposed system employs active RFID technology to estimate the location of users/objects, and ZigBee to build a P2P network for communication purposes. It can be used for various purposes, such as asset management and customer relationship management. In summary, this research makes four major contributions. First, the proposed system using a P2P architecture can facilitate system setup and management. Second, a communication protocol for ZigBee and RFID is presented. Third, we investigate some position estimation methods using radio signal strength, reference tags, and a simple formula with dynamic parameters calibration for the positioning

system. Lastly, we present experimental results, which give valuable insights into the design of an RFID-based position estimation system.

Publications

Terry H. S. Chu, **Felix C. P. Hui**, and Henry C. B. Chan, Smart Shopping System Using Social Vectors and RFID, The 2013 IAENG International Conference on Computer Science, IMECS2013

Felix C. P. Hui, Henry C. B. Chan, and S. H. Fung, RFID-based Location Tracking System Using a Peer-to-Peer Network Architecture, The 2014 IAENG International Conference on Computer Science, IMECS2014

Felix C. P. Hui and Henry C. B. Chan, Position Estimation Methods for an RFID-based Positioning System with a P2P Network Architecture, European Wireless 2014

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Chapter 1. Introduction

In recent years, there has been considerable interest in developing location or position tracking systems. Generally, such systems can be classified into indoor and outdoor systems. For outdoor location tracking, the Global Positioning System (GPS) is the most commonly used technology. Funded and developed by the Department of Defense (DoD) of the United States, it has been in use since the mid-1990s [1]. Essentially, in GPS, a receiver uses satellite signals to estimate its position (e.g., for navigation purposes [2]). Cellular communications offer an alternative outdoor location tracking solution [3]. Here, the communications signals transmitted between the base stations and the mobile terminals are used to estimate the location of a mobile terminal. However, GPS and cellular communications cannot be employed in an indoor environment and may not work well in urban areas because signal reception can be affected by tall buildings.

For indoor location tracking systems, Wi-Fi and RFID are two major technologies that can be used. Both can be employed to perform location estimation using such methods as Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and fingerprint methods [4, 5, and 6]. The popularity of

WLANs has led to WLANs becoming common communications infrastructure in commercial buildings and indoor environments such as shopping malls, coffee shops, hotels, and airports. Existing WLANs infrastructure makeS it possible for indoor location tracking systems to be developed without the installation of additional networking equipment [7]. For this reason, Wi-Fi-based location tracking techniques have become commonly used solutions for indoor environments. However, a Wi-Fi-based solution requires not only Wi-Fi-based infrastructure but also Wi-Fi-supported user devices, which may be costly under certain circumstances. For example, a Wi-Fi-based solution may not be cost-effective for tracking the location of objects or the locations of a large number of users without Wi-Fi devices.

RFID can provide an alternative solution to the use of Wi-Fi. In recent years, RFID has been widely used in different areas [8] such as object management [9], retailing [10], logistics [11, 12], and transportation monitoring [13]. Due to the growing demand for RFID for various indoor applications (e.g., for supporting a warehouse system [14]), it is of interest to study the use of RFID for indoor location tracking. Compared with Wi-Fi devices, RFID tags are cheaper and can provide similar functions more cost-effectively.

However, unlike Wi-Fi, where the infrastructure is often pre-installed, an RFID-based location tracking system requires additional equipment.

Employing a Peer-to-Peer (P2P) network would be a desirable solution to make an RFID-based tracking system more practical and effective. A P2P network is basically a distributed network, which operates through collaboration among the network nodes [15]. In a P2P network, computers or devices can interact with each other in a direct and flexible manner. Unlike traditional networking or client/server approaches, communications can be conducted and information can be exchanged on an ad hoc basis [15]. For instance, Guntella is a popular file sharing system that operates using a P2P network [16, 17]. And some researchers have already applied P2P with RFID technology [18].

In this research, the aim is to design a Peer-to-Peer RFID-based location tracking system. There are three major objectives:

i. To design the general system architecture

ii. To design the location tracking mechanism

iii. To design the basic communication protocols

In the proposed P2P RFID-based location tracking system, all readers will represent a node and be connected to at least one other reader to form a P2P network. With the use of the ZigBee protocol, the network can be formed easily and new nodes can be joined using a simple procedure. Data can be easily exchanged. In summary, a P2P-based system facilitates system installation, technical maintenance, and future expansion.

Chapter 2. Literature review

2.1. RFID technology

RFID is one of the potential technologies used to develop indoor location tracking system. Besides RFID, there are many other technologies available such as Infrared [19], Bluetooth [20], and wireless local area network (WLAN) [21]. RFID is a wireless technology that allows users to identify objects or people using RFID tags. An RFID system is essentially comprised of three main components: tags, readers, and host computer(s). RFID tags can either be active or passive. An active RFID tag is equipped with a battery. Unlike a passive RFID tag, an active RFID tag can continuously emit radio signals (i.e., conveying identity information). Some active RFID tags can store data and even be embedded with sensors to perform enhanced functions (e.g., convey environmental information) while embedding sensor to passive tag is a challenge previously [22] but there are some successful cases [23]. In this project, active RFID tags are used for the system. To read RFID tags, RFID readers are required. An RFID reader has two major components: an antenna for sending and receiving radio signals and an electronic module for data processing and communication purpose. RFID readers are typically connected to a host computer for processing information and performing various management functions [24]. In recent years, RFID systems have been widely deployed in different industries or areas of application and location information would be one of the important advance functions to improve those applications such as [25]. While RFID has been designed for identification purposes, it can also be employed for location tracking or position estimation purposes [26].

Fig. 1 Active RFID reader

Fig. 2 Active RFID tag

2.2. Location techniques

To perform location estimation, there are many different mechanisms and one of the most commonly used methods is based on the distance estimation. With the estimated distances, location can be also estimated using trilateration. To estimate the distance, Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Received Signal Strength Index (RSSI) are commonly used. The remaining of this section will introduce those mechanisms which also include other mechanisms such as based on Angle of Arrival (AOA) and Fingerprint.

2.2.1. TOA

Time of Arrival (TOA) [7] is based on the time taken for a radio signal transmitted between transmitters and receivers. Since radio signals are electromagnetic signals, their speed are the same as the speed of light which is approximately 3×10^8 meters per seconds. Thus we can estimate the distance between the transmitter and receiver directly by timing information. By applying the concept of trilateration using three sets of distance data, the location of an object can be estimated. In TOA, the result depends highly on the accuracy of the time measurement and the synchronization of the system.

2.2.2. TDOA

One problem faced by TOA is that it requires a synchronized time between receivers and transmitters, which is particularly problematic for mobile devices. The problem is significant because a small error in time measurement would lead to a very large error because of the high signal propagation speed (e.g., a nanosecond error will cause around 0.3 meter error in the distance estimation).

Time Difference of Arrival (TDOA) [7] differs from TOA which synchronized time source is not required. Instead of TOA, TDOA makes use of the relative time measurements [27]. In TDOA, time synchronization is only required between the receivers which will receive the signal with an unknown starting time. The concept is depicted in Fig.3 below. When the source object X transmits a message, this message reaches receivers A, B, and C with the recorded time T_A, T_B and T_C respectively. $TDOA_{B-A}$ represents the time difference of arrival between A and B. We can then conduct the difference of distance between A and B which could form a hyperbola with foci at A and B. Another hyperbola with foci at A and C can be formed similarly. Finally, the intersection of two hyperbolas provides an estimated location of the source object. This is also called hyperbolic lateration.

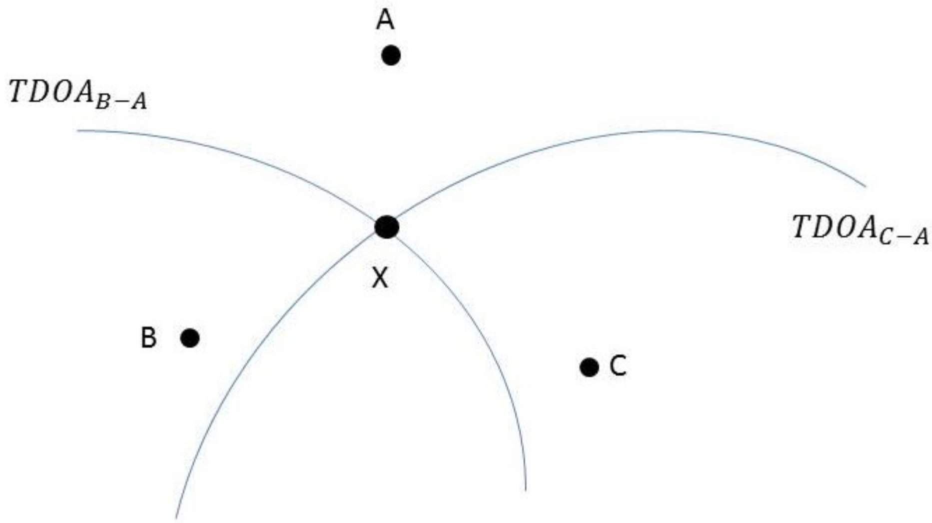


Fig. 3 Time Difference of Arrival

2.2.3. RSSI

Another approach for location estimation does not involve time measurement. For example, Received Signal Strength Index (RSSI) [7] can also be used to perform lateration to estimate the target object's location [28]. According to the physical property of radio waves, we can apply a common path loss model of radial propagation. In wireless communication, path loss normally represents the loss in signal strength of a radio wave transmitting through free space, while RSSI is the received signal strength index of the signal when it is received and measured by a receiver. In the path loss model, we have to consider all the related parameters such as frequency of the radio wave, transmission output power, cable loss, antenna gain and etc. We can then estimate the distance according to the corresponding RSSI value and apply trilateration to estimate the object location.

2.2.4. AOA

Angle of Arrival (AOA) [29] is also known as Direction of Arrival (DOA). It uses the angle of incidence when the signal reaches the receiver to determine the source device. By forming two lines of bearing (LOBs) from each receiver, the location of source device can be estimated (refer to Fig. 4). This is known as triangulation. However, AOA requires directional antennas which would make the system become less convenience.

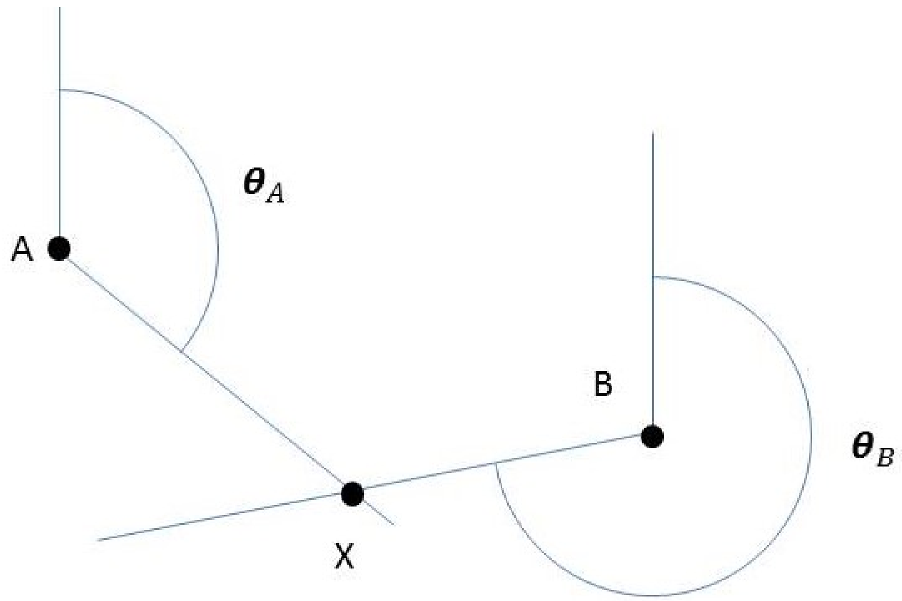


Fig. 4 Angle of Arrival

2.3. Location tracking system

Some location estimation mechanisms are introduced in the previous section. Some of them have been already used to develop a prototype or preform testing by researchers. We shall now discuss some representative location tracking systems and approaches.

2.3.1. Outdoor location tracking using RSSI

In [30], a new approach is proposed for locating and tracking object base on RSSI. Three approaches are proposed to be used (three base stations, five base stations and seven base stations respectively) with three propagation models (Okumura-Hata model [31], UMTS-30.03 macro model [32] and Long-distance model [33]) for estimating the location of the RFID tag. In the simulation, an active tag was attached to the person or object which is going to be tracked. By measuring the RSSI from the tag, the location of the tag can be estimated. The proposed system was applied to a security application and studied as an example. It allows security officers to track and monitors the tagged person or object in Mosul university campus. In the study, a series of simulation was performed to locate lost object's location around a base station. Their simulations suggested that the result measured by 7-BS's with macro model can provide the lowest rms-error. Thus, it is concluded that macro model with more base stations could give better location estimation results. One of the key conclusions of this research is the rms-error can be improved by using more base stations.

2.3.2. RADAR

RADAR [34] is a RF based location tracking system for an indoor environment which has a similar concept with the Fingerprint because it has to collect several data before performing location estimation. In the RADAR system, it includes two phases, off-line phase and real-time phase (see Fig. 5). Off-line phase is the data collection phase which records the radio signal information including the location, signal strength, and time. During the real-time phase, same kinds of data will be collected and be used to comparing with the database, hence tracking the location of the target object after series of processes.

For each data collection, each base station will measure the signal strength of the radio signal and record the timestamp. Thus, each dataset includes three major data, base station, signal strength and timestamp. The clock of the base station and mobile source are required to be synchronized since the timestamp is one of the data to be collected. In the experiment, there are seventy locations during the off-line phase and data is record in four different orientations (one of east, south, west and north). Therefore, two hundred and eighty sets data are recorded.

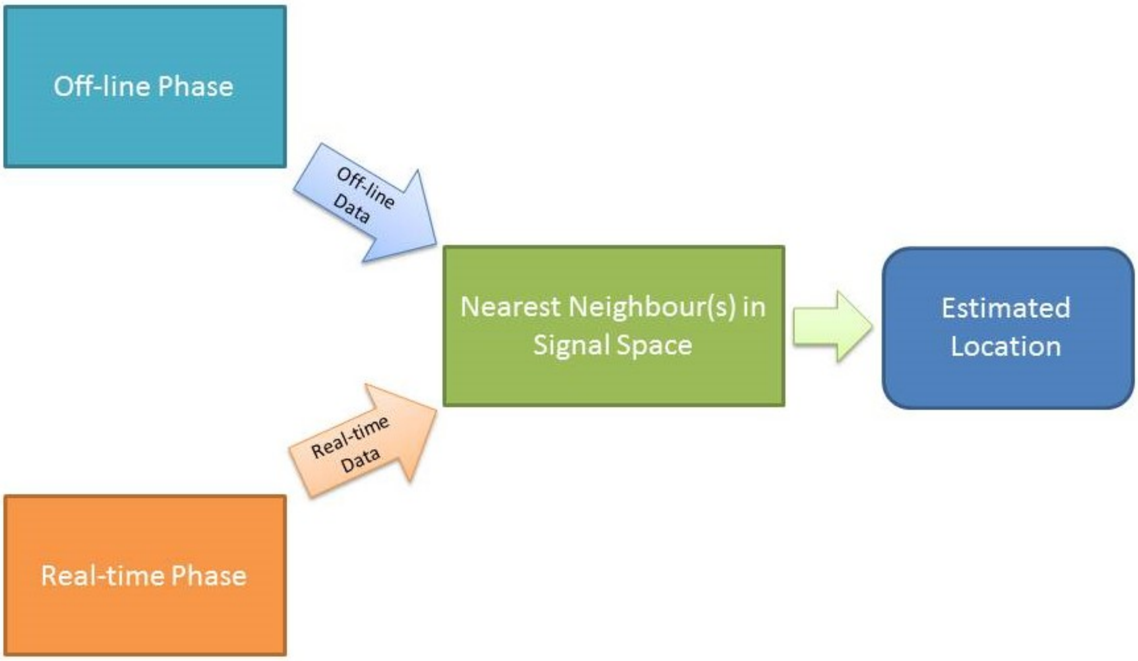


Fig. 5 Estimation flow chart of RADAR

During analysis, author uses the nearest neighbour(s) in signal space (NNSS) as the technique to search and pick location as the estimation which best matches with the recorded real-time data. Although RADAR can estimated the location of the tracked object, the data collection phase and synchronized time would be the difficulty of this system.

2.3.3. LANDMARC

A prototype of location sensing system inside buildings for locating object using RFID technology called LocAtioN iDentification based on dynaMic Active Rfid Calibration (LANDMARC) is presented in [35] which would be the first indoor location system using active RFID. LANDMARC improved the overall accuracy of the location estimation using the reference tags method. Previously, more readers should be used to improve the accuracy. However, as a reader is more expensive than a tag which make the location tracking system become less cost-effective. Thus, instead of readers, tags are proposed to be used for providing support to calibrate the estimation. In LANDMARC, several tags are placed at different reference points which act as landmarks. Those reference tags experience the same effect by environmental factors as normal tags experienced. Those data from the reference tags can provide a helpful reference offset to the received data of tracking tags. The research in [35] also pointed out that the placement of reference tags and readers will effectively affect the overall accuracy. In the experiment, it is concluded that some of the environmental factors can be calibrated with the LANDMARC but it is not guaranteed that all the RFID tags are being affected equally by the dynamic environment which is still one of the major reasons leading a measurement error.

2.3.4. Improved LANDMARC

Based on the concept of LANDMARC, another team of researchers from the Cheng-Shiu University introduced a new methodology with higher accuracy based on the same set of equipment but using fewer reference tags. They proposed that by adding a weighting to the reference could improve the accuracy [36] which can also reduce the quantity of reference tags. Sixteen reference tags are used in LANDMARC, but they are now placed in larger area than previously (twenty meters by twenty meters instead of four meters by nine meters). Using the principle of geometry, it can reduce the possible estimated ranges of the tracked tag. As an example, refer to the following Fig. 6

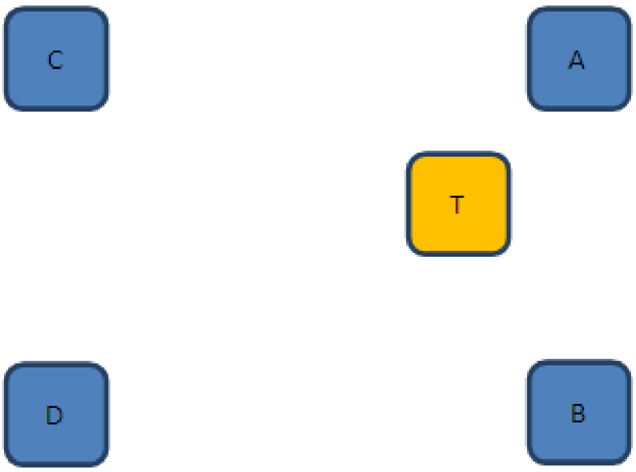


Fig. 6 Weighting reference tag method

If a tracked tag T falls in the region bounded by 4 reference tags: A, B, C, and D, a weighting value is computed according to distance between tracked tag and reference tags. Suppose the data shows that the distance between T and four reference tags are denoted by TA, TB, TC, and TD respectively, where TD > TC > TB > TA. A rectangle ABDC can be drawn out which represents the region of the tracked tag is believed to be located. To minimize the size of this region in order to provide a more accurate position of the tracked tag T, it is proposed to draw a diagonal between B and C which reduces the area by half (refer to Fig. 7). After that, draw another diagonal between A and D which reduces the area by half again (refer to Fig. 8). Thus, the estimated region could be reduced to one fourth.

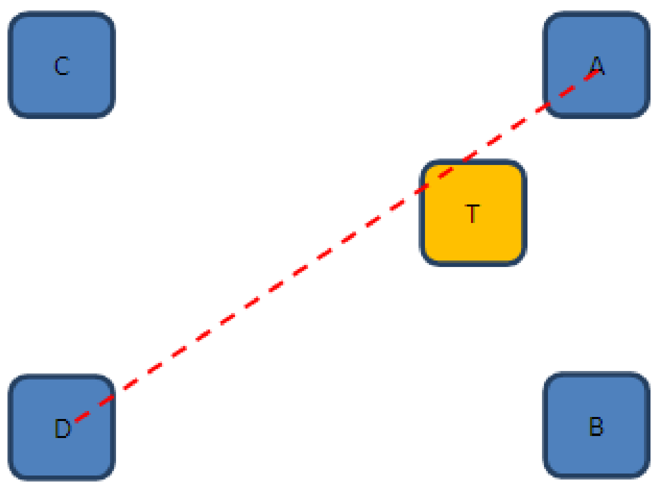


Fig. 7 Diagonal BC reduces the area into half

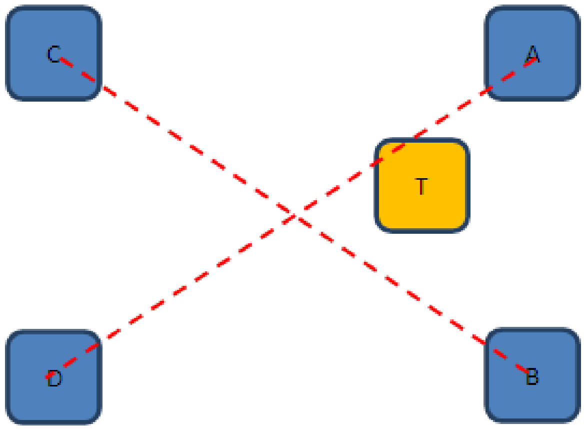


Fig. 8 Diagonal AD reduces the area into half again

2.3.5. VIRE

Since LANDMARC approach has two important drawbacks which are the multi-path effects and the high cost for improving the accuracy, a new approach called Virtual Reference Elimination (VIRE) is proposed in [37] which can overcome those drawbacks. The idea was to add some virtual reference tags inside the coverage area based on the LANDMARC approach. Each area was bounded by four physical reference tags (see Fig. 9) and further divided into *n* by *n* equal sized grid cells (see Fig. 10). The coordinates of each grid cells can be found using the coordinates of four physical reference tags. After that, those virtual reference tags are assigned with RSSI values using linear interpolation algorithm. Finally, the testing results showed that VIRE approach can enhance the performance from the range of seventeen to seventy three percent compared to LANDMARC approach.

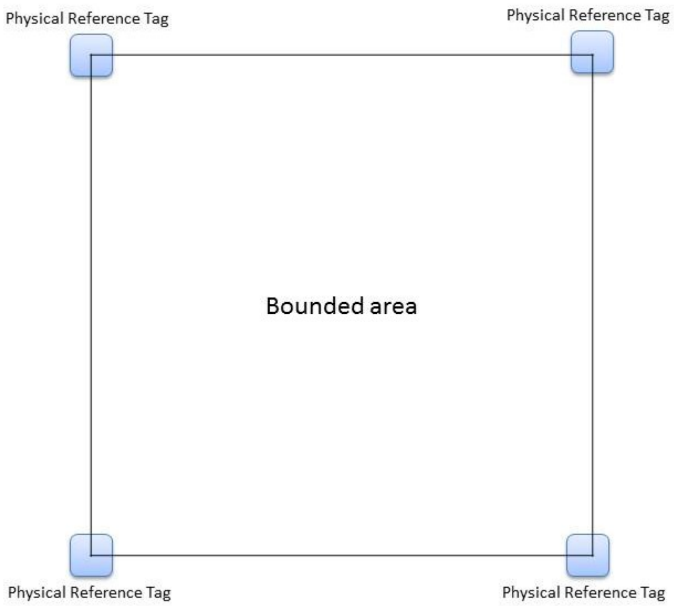


Fig. 9 Area bounded by four physical reference tags

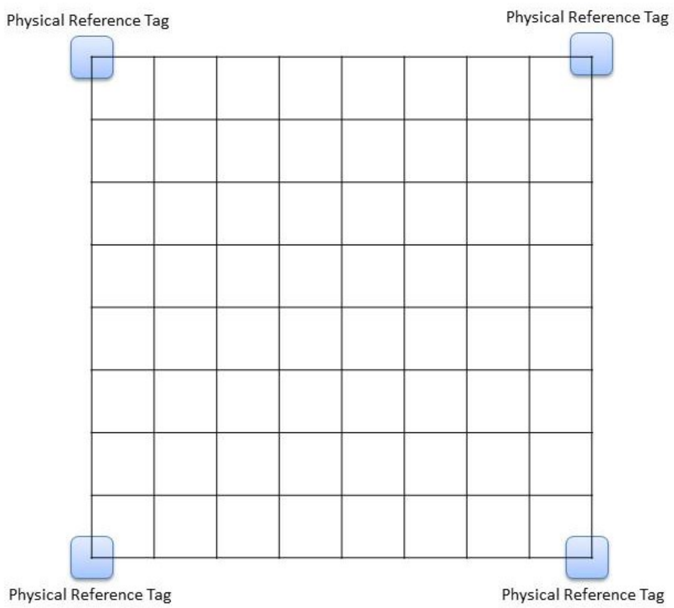


Fig. 10 Further divide the bounded area

Chapter 3. System overview

In traditional active RFID systems, most of the communications can be set up by connecting them with cables such as LAN cables or Comport cables. Since physical connection may increase the implementation cost and difficulty. In recent years, active RFID systems have also been implemented using a Wi-Fi-based infrastructure. IEEE 802.11b/g is one of the most common standards being used for wireless connection which can make use of the advantage of WLANs. Also, web interface is always a common interface for setting up the wireless connection which is similar to the router set-up. In general, this set-up method has to be done on every reader individually. This kind of system set-up progress is still complex for users which always need the system provider to provide set-up and maintenance service. In another word, this kind of wireless reader cannot reduce the cost of the system significantly.

In this research, we present a more flexible active RFID system using a P2P network architecture. No more physical cable and complex set-up process are needed. The proposed system can be set-up those a few simple steps.

3.1. General architecture

The system architecture of the RFID-based location system makes use of a 2.4GHz ZigBee to build the P2P network architecture. Fig. 11 shows the general architecture of the system. This architecture includes three major elements: master, node and tag. The tag is a 2.4GHz active tag, which has a reading range around 50 meters and will be attached to a tracking object. Each node is an active RFID reader that communicates with the tags and the master. All the nodes will be placed and fixed in the tracking region for reading the RFID tags. The master is a gateway that works as a backend server. It is connected to the computer and performs data collection and network management. Also, it can be moved within the tracking area which can connect to one of the nodes. The node and master have same reading range with is about 80 meters.

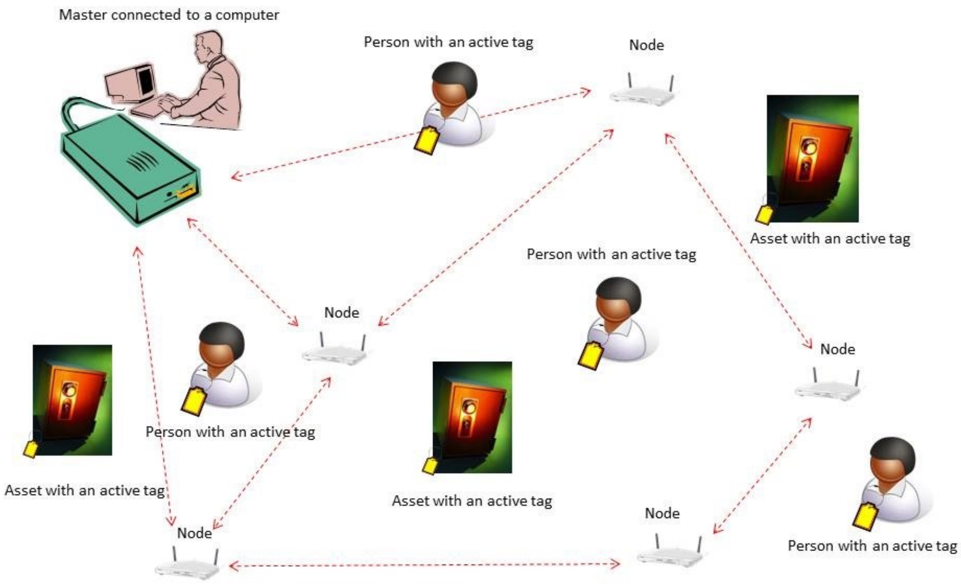


Fig. 11 General system architecture

With this architecture, physical cables can be minimized and installation procedures can be simplified. Also, the system coverage can be easily expanded by adding more nodes. The next sub-section contains an introduction of how to set up the network.

3.2. Communications protocols

The communications protocol for the P2P network is presented in this sub-section. In the P2P RFID-based location tracking system, an Active RFID reader with ZigBee communications capability serves as a node in the P2P network. In other words, this reader contains not only an RFID module but also a ZigBee module. Different from a node, the master only contains a ZigBee module since it only communicates with a node through the ZigBee-based communication protocol. We denote T_i as the tag *i*, N_j as the node *j*, and M as the master. According to the communication flow as shown in Fig. 12, tags communicate with nodes using RF packets while nodes communicate with the master using ZigBee packets. When the nodes transfer an RF packet to the master, the nodes have to repack the RF packet into a ZigBee packet. However, the original RF packet does not need to be modified or changed during the repacking process. The RF packet is directly fitted into the ZigBee packet. This also makes it possible for the system to be compatible with various active RFID systems.

As shown in Fig. 12, two major types of ZigBee data packets are used in the P2P RFID-based location tracking system. Using these two types of packets, the RF module can interface with the ZigBee module while the ZigBee module can transmit these packets through the ZigBee communications protocol.

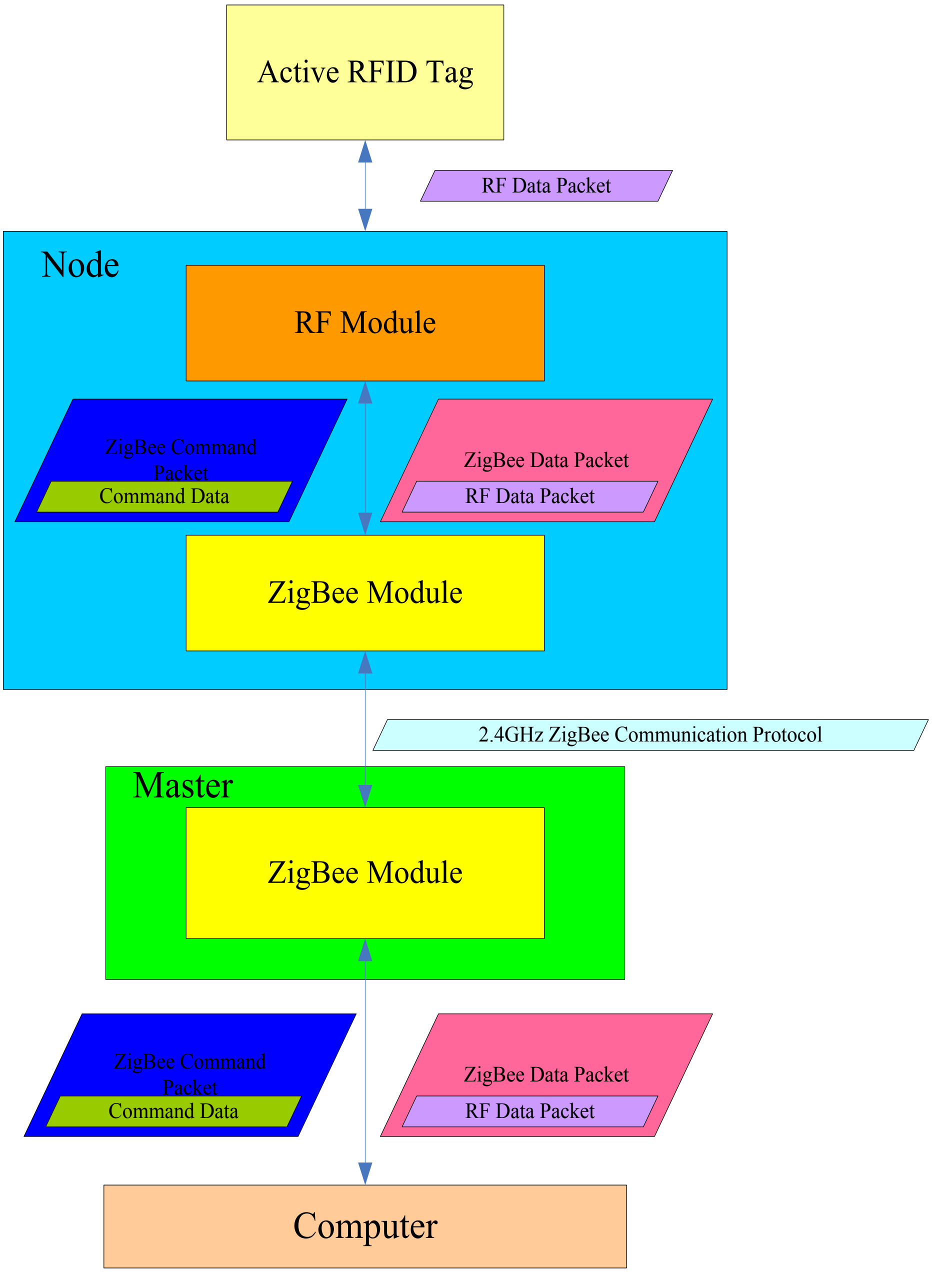


Fig. 12 Basic communications protocol

Referring to Fig. 12, ZigBee data packets basically allow users to manage and communicate with each node in the network using a specific RF data packet. The RF data packet can be customized by the developer, which means that it can be used to support various active RFID systems. Note that the original RF data packet of the RFID system can be directly fitted into the ZigBee data packet without any modifications. That means, for example, company A has its own RF data packet X_1 while company B has its own RF data packet X_2. Both of them can insert X_1 or X_2 into the ZigBee data packet without modifying the original structure. Apart from ZigBee data packets, ZigBee command packets (see Fig. 12) are used for system/network control purposes. In particular, various commands can be defined for the Node Discovery and Neighbour Discovery processes. These are two important processes that will be discussed in the next section. In summary, active RFID tags communicate with the nodes using a specific RF data protocol. Nodes and the master communicate using the ZigBee communications protocol. Essentially, RF data packets are embedded inside ZigBee packets for data transfer purposes. The master can also control the nodes through various commands, which are conveyed through the P2P network using ZigBee packets.

3.3. Peer-to-peer network

Once the master and the nodes are powered up, two commands are used to set up the network:

Node Discovery	Find all nodes within the master's reading range
Neighbour Discovery	Ask the nodes to report the neighbour nodes that lie within their own reading range

Node Discovery helps users find all nodes within the master's coverage area. Once the master discovers all of the nodes around itself, the master can ask each node to report their neighbour nodes by sending the Neighbour Discovery command. This step also helps to ensure that no node is missing when the network is so large such that some nodes are out of the master's coverage.

Fig. 13 shows an example of a network. In Fig. 13, the master is connected to a computer and there are five nodes ($\text{i.e.}, N_1, N_2, N_3, N_4, \text{and } N_5$). Suppose that the master only discovers $N_1, N_2, \text{and } N_3$, which are connected with red dashes. In order to connect with other nodes ($\text{i.e.}, N_4 \text{ and } N_5$), a Neighbour Discovery command should be sent to $N_1, N_2, \text{and } N_3$. Thus, N_1 should discover $N_2 \text{ and } N_4$, which in Fig. 13 are connected by blue dashes. Similar to N_1, $N_2, N_3, N_4,$ and N_5 should discover their neighbours. Finally, a full network relationship is found and shown in Fig. 14.

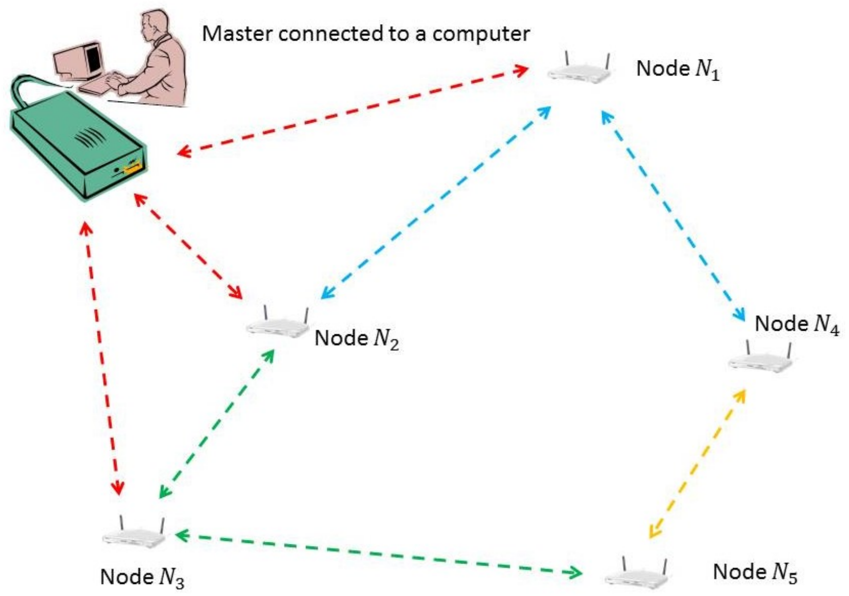


Fig. 13 Network Example

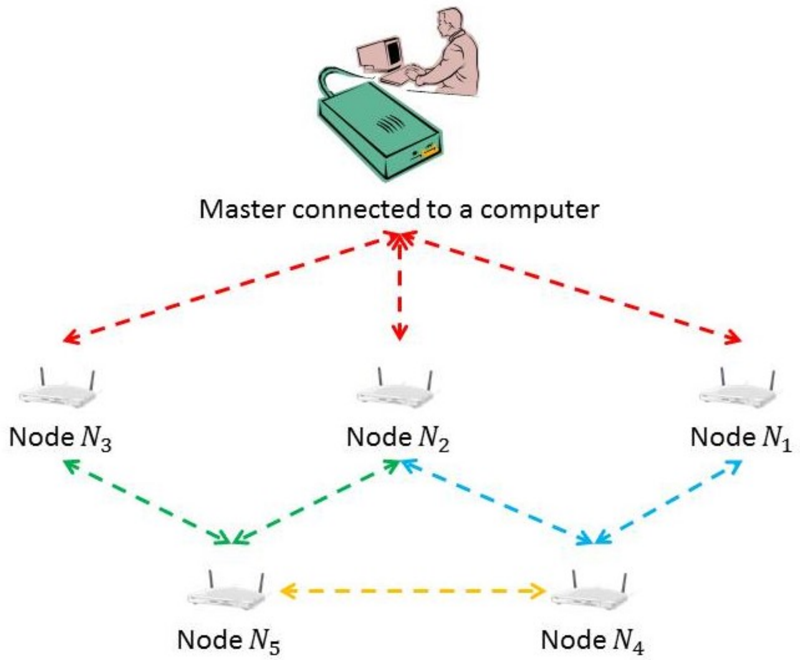


Fig. 14 Network Relationship

The Node Discovery and Neighbour Discovery are compulsory steps for setting up the P2P network and for adding more nodes to the system. After the network is set up, the nodes initially stay in the idle mode (i.e., they will not identify the tags). To start identifying the tags, the master should send a "Start Read" command, which will be propagated to every node. Once a node receives the command, it will shift to the listening mode. During the listening mode, a node will listen to RF data (i.e., identifying the tags) and make appropriate measurements (e.g., RSSI values). Periodically, each node will pass the tag information to the master through the P2P network. Having obtained all of the tag information from the P2P network, the master/computer will perform distance estimation and location estimation. Fig. 15 shows a summary of the aforementioned process.

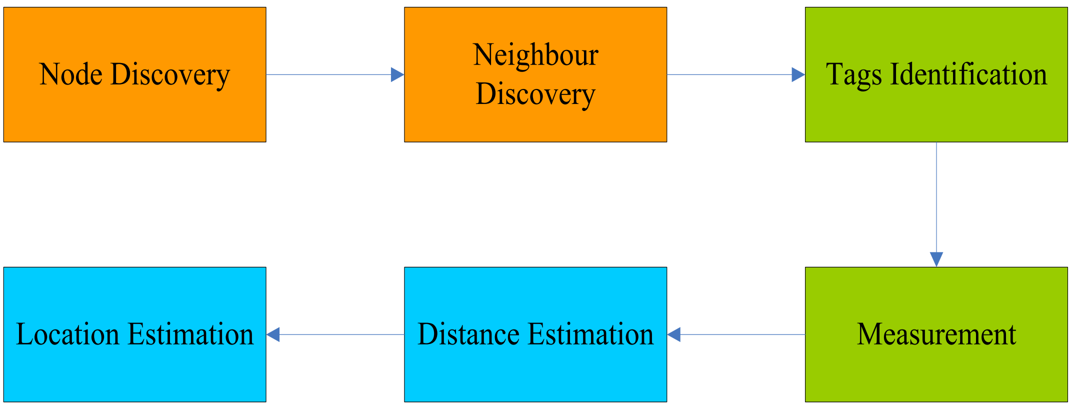


Fig. 15 Process Overview

Chapter 4. Location tracking mechanism

Major RFID location tracking mechanisms include RSSI, TOA, TDOA, and fingerprint methods to perform distance estimation. With the estimated distances, the location can be calculated by means of the trilateration method (see Fig. 16). Specifically, given three distances d_1, d_2, and d_3 from corresponding origins (x_1, y_1), (x_2, y_2), and (x_3, y_3), there could be an interception point (h,k), such that,

$$(h - x_1)^2 + (k - y_1)^2 = (d_1)^2 \tag{1}$$

$$(h - x_2)^2 + (k - y_2)^2 = (d_2)^2 \tag{2}$$

$$(h - x_3)^2 + (k - y_3)^2 = (d_3)^2 \tag{3}$$

TOA basically measures the travelling time of the radio signal to perform distance estimation. Note that the velocity of the radio signal is known as the speed of light, which is 3×10^8 m/s. However, TOA requires time synchronization in all of the devices. As an enhancement, TDOA was developed as an alternative to TOA. In essence, TDOA measures the time difference of the radio signal. By doing so, there is no need to synchronize the sender and receiver to facilitate implementation.

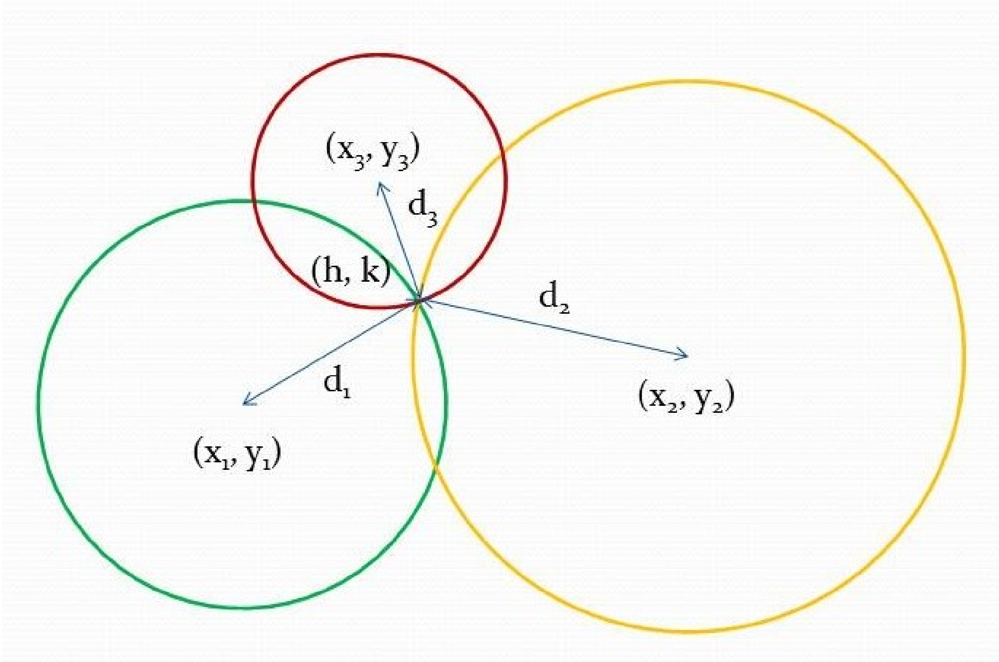


Fig. 16 2D Trilateration

Another location tracking method is based on RSSI. In this method, the assumption is that there is a relationship between radio signal strength and distance. For example, using the Free Space Path Loss (FSPL) model of electromagnetic wave propagation, the distance can be estimated based on RSSI. Hence, similar to the process described above, the location of a tag can be determined by the aforementioned trilateration method [38] using the estimated distances. A more accurate location tracking technique is the fingerprint method [39]. However, a training phase is required to obtain measurements for fingerprint method. In this project, we use RSSI method for distance estimation and the reference tag method for calibration.

RSSI values can be affected by environmental conditions such as multi-path effects, distortion by obstacles etc. However, the reference tag method can provide information on the effect of the environment to calibrate the system, it is used to calibrating the FSPL model in the proposed system. In the system, there are tracking tags, reference tags, nodes, and the master. Tracking tags are active RFID tags which are tagged on any objects or humans. Reference tags are also active RFID tags which are same as the tracking tags, but used to provide data for calibrating the system. At least two reference tags and three nodes are required in the proposed system to perform estimations. To estimate the location of the tracking tag, reference tags can provide information for calibrating the system. The estimated distance between the tracking tag and each node can then be obtained. With the estimated distance and the locations of the nodes, the estimated location of the tracking tag can be computed. Fig. 17 shows the flow of the estimation. Details of the methodology are given in the remainder of this section.

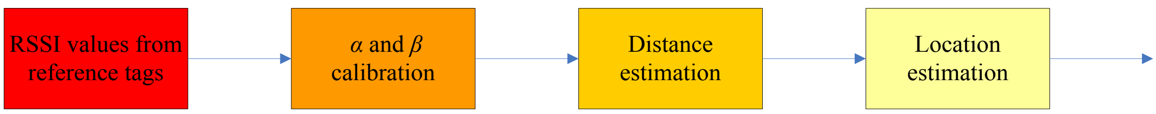


Fig. 17 Estimation flow

4.1. Methodology

In the FSPL model [40], an electromagnetic wave or signal will propagate uniformly in free space. Hence, its energy will radiate in the form of a sphere. According to the law of the conservation of energy, the power density of the electromagnetic wave will be inversely proportional to the square of the distance from the transmitting source. Thus, the distance can be computed by the FSPL using the Friis transmission equation [41] if the propagation path is in a free space.

Based on [40], defining F as the ratio of the transmitted power to the received power, we have

$$F = \frac{P_s}{P_d} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{4}$$

$$F = \left(\frac{4\pi d f}{c}\right)^2 \tag{5}$$

where d denotes the distance between the transmitter and the receiver

f denotes the frequency of the RF signal

c denotes the speed of light

P_s denotes the transmitted power

P_d denotes the received power.

Also, we have

$$10\log_{10}(F) = 10\log_{10}\left(\frac{P_s}{P_d}\right) \tag{6}$$

$$10\log_{10}(P_d) = RSSI = 10\log_{10}(P_s) - 10\log_{10}(F) \tag{7}$$

From (5), we have

$$10\log_{10} F = \ 10\log_{10}\left(\frac{4\pi df}{c}\right)^2 \tag{8}$$

$$10\log_{10} F = 20\log_{10}(4\pi df) - 20\log_{10}(c) \tag{9}$$

Substituting (7) into (9), we have

$$RSSI = -20\log_{10}(d) + K \tag{10}$$

where

$$K = 10\log_{10}(P_s) - 20\log_{10}(4\pi f) + 20\log_{10}(c) \tag{11}$$

This means that, theoretically, RSSI should have a linear relationship with log(*d*). Note that, in practice, we also need to take into consideration other factors (e.g., antenna gain).

In order to test whether RSSI has a linear relationship with log*(d)* several indoor and outdoor experiments were conducted. The results are compared and shown in Fig. 18

(i.e., RSSI is plotted against log*(d)*). The results show that (12) can provide a reasonable relationship between RSSI and log*(d)*:

$$RSSI = \alpha \log_{10} d + \beta \quad (12)$$

where α and β are constants.

In the proposed system, the values of α and β may vary due to environmental effects and they are calibrated before conducting location estimation. By determining the values of α and β, the distance can be estimated. After obtaining the estimated distances from three readers, the location of a tag can be estimated by applying the trilateration method.

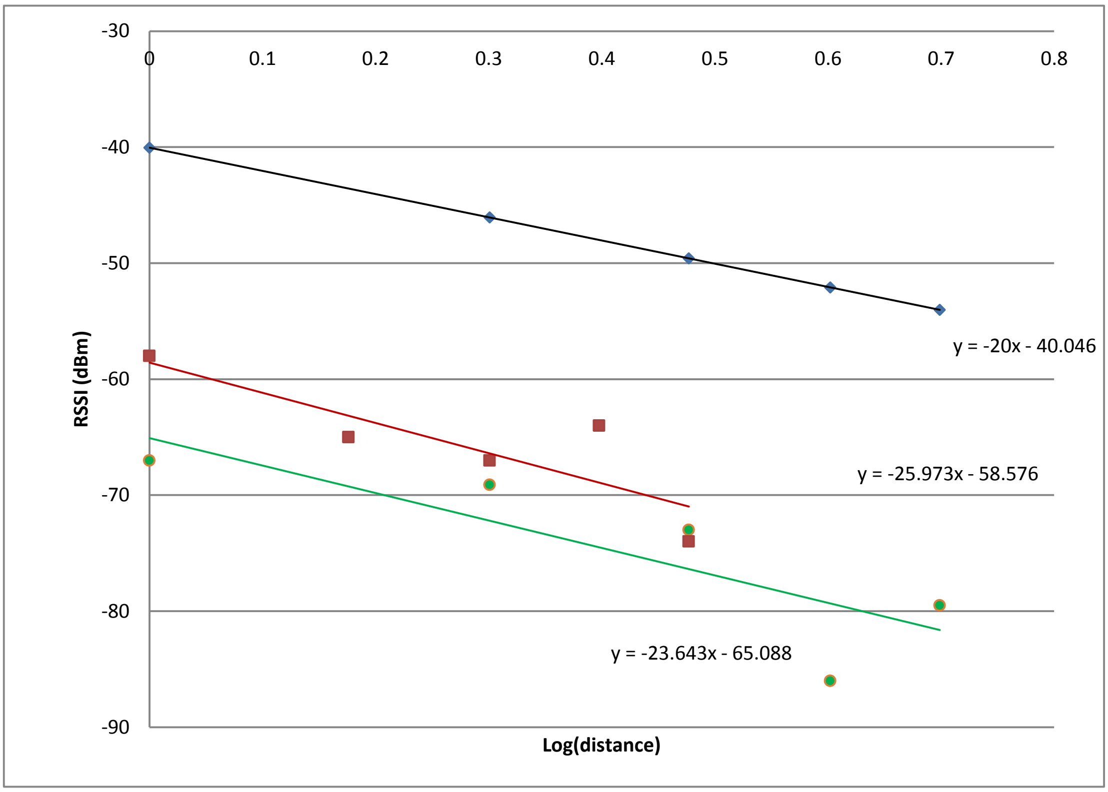


Fig. 18 RSSI Value Comparison

4.1.1. Distance Estimation

Fig. 18 and (12) shows a linear relationship between the RSSI value of the signal from the tag and the logarithm of the distance between the tag and the node. Although FSPL is only valid in a free space environment, the testing result in Fig. 18 shows that (12) provides a reasonable estimation in general. In (12), α and β are basically dependent on the frequency of the RF signal, the speed of light, the transmitter antenna gain, the receiver antenna gain, and possibly various environmental factors.

In the proposed approach, the reference tag method is used to calibrate the value of α and β. For each distance estimation of tracking tag *i*, a group of reference tags provides important RSSI values for the system to calibrate the value of α and β. For estimating the distance between node *j* and tracking tag *i*, α_{ij} and β_{ij} are defined as a specific set of α and β values for node *j* to apply in (12). Thus, (12) can be rewritten as:

$$\gamma_{ij} = \alpha_{ij} \log_{10} \theta_{ij} + \beta_{ij} \tag{13}$$

where γ_{ij} is the RSSI value of tracking tag *i* received by node *j*

θ_{ij} is the distance between tracking tag *i* and node *j*.

Since the RSSI value of reference tag k is measured by node j and the distance between node j and reference tag k is known, α and β are two remaining unknown values in (12). The simplest method for computing the values is to solve the simultaneous equations by using two reference tags to provide two sets of RSSI values and distances, which are represented as follows:

$$\begin{cases} \tau_{pj} = \delta_{pqj} \log_{10} \phi_{pj} + \omega_{pqj} \\ \tau_{qj} = \delta_{pqj} \log_{10} \phi_{qj} + \omega_{pqj} \end{cases} \tag{14}$$

where τ_{pj} is the RSSI value of reference tag *p* corresponding to node *j*,

ϕ_{pj} is the distance between reference tag *p* and node *j*,

δ_{pqj} is the α value of node *j* corresponding to reference tags *p* and *q*,

ω_{pqj} is the β value of node *j* corresponding to reference tags *p* and *q*.

To obtain more data for the calibration process, more reference tags should be used. For *n* reference tags, the value of α and β of node *j* will depend on two vectors τ_{j} and ϕ_{j}, which are represented as follows:

$$\tau_{\mathrm{j}} = \left(\tau_{1j}, \tau_{2j}, \dots, \tau_{nj}\right) \tag{15}$$

$$\phi_{\mathrm{j}} = \left(\phi_{1j}, \phi_{2j}, \dots, \phi_{nj}\right) \tag{16}$$

In the next part of this section, three approaches are introduced to make use of τ_{j} and ϕ_{j} for calibrating the value of α and β.

4.1.1.1. Averaging Algorithm

For each pair of reference tags *p* and *q*, a set of corresponding values $\left(\delta_{pqj},\ \omega_{pqj}\right)$ can be computed by $\left(\tau_{pj},\ \log_{10}\phi_{pj}\right)$ and $\left(\tau_{qj},\ \log_{10}\phi_{qj}\right)$. If *n* reference tags are used in the system, the C_2^n set of $(\delta,\ \omega)$ can be obtained. By taking the average, the following are obtained:

$$\alpha_{\mathrm{ij}} = \frac{1}{C_2^n}\sum\nolimits_{p=1,}^{n-1}\sum\nolimits_{q=p+1}^{n}\delta_{pqj} \tag{17}$$

$$\beta_{\mathrm{ij}} = \frac{1}{C_2^n}\sum\nolimits_{p=1}^{n-1}\sum\nolimits_{q=p+1}^{n}\omega_{pqj} \tag{18}$$

Details are shown in Algorithm 1.

Algorithm 1: algorithm for calibrating *α* and *β* for estimating the distance using Averaging Algorithm

Input: locations of nodes

locations of *n* Reference tags $(R_1, R_2, \ldots, R_n)$

RSSI values of reference tags

Output: α and β of the node $(\alpha_{avg},\ \beta_{avg})$

1: **declare** a database table *table_ref* to store the data of reference tags

2: **declare** columns TagID, RSSI, Location, and Distance for the database table

table_ref

declare a list *list_AB* to store temporary α and β value

declare variables α_{avg}, β_{avg}

update *table_ref* column Distance using the location of the reference tags and node

for each reference tag in *table_ref* **do**

  select reference tag *RT_A* from *table_ref*

  for each reference tag in *table_ref* **do**

    select reference tag *RT_B* from *table_ref* where *RT_A* not same as *RT_B*

    use *RT_A* and *RT_B* to form a simultaneous equation according to equation (14)

    solve the simultaneous equation to obtain temporary α and β value

    store temporary α and β value into *list_AB*

  end for

end for

compute the average α and β value from *list_AB*

store the result in α_{avg}, β_{avg}

output α_{avg}, β_{avg}

4.1.1.2. Trendline Algorithm

As the RSSI of the tags and its corresponding distance can perform a linear trend as shown in (12), it is assumed that the data set (τ_{j} ,$\log_{10} \phi_j$) can also perform a linear trend with slope δ_j and y-intercept ω_j such that:

$$\tau_j = \delta_j \log_{10} \phi_j + \omega_j \tag{17}$$

According to [42], let

$$A = n \sum_{h=1}^{n} \left(\log_{10}\phi_{hj} \times \tau_{hj}\right) \tag{19}$$

$$B = \sum_{h=1}^{n} \log_{10}\phi_{hj} \times \sum_{k=1}^{n} \tau_{kj} \tag{20}$$

$$C = n \sum_{h=1}^{n} \left(\log_{10}\phi_{hj}\right)^2 \tag{21}$$

$$D = \left(\sum_{h=1}^{n} \log_{10}\phi_{hj}\right)^2 \tag{22}$$

Thus, slope δ_j can be obtained by:

$$\delta_j = (A - B)/(C - D) \tag{23}$$

Then, let

$$E = \sum_{k=1}^{n} \tau_{kj} \tag{24}$$

$$F = \delta_j \sum_{h=1}^{n} \log_{10}\phi_{hj} \tag{25}$$

Therefore, y-intercept ω_j can be computed by:

$$\omega_j = (E - F)/n \tag{26}$$

By substituting $\alpha_{ij} = \delta_j$ and $\beta_{ij} = \omega_j$ into (13), the distance θ_{ij} between tracking tag *i* and node *j* can be estimated. Details can refer to Algorithm 2.

Algorithm 2: algorithm for calibrating α and β for estimating the distance using Trendline Algorithm

Input: locations of nodes

locations of n Reference tags ($R_1, R_2, \dots, R_n$)

RSSI values of reference tags

Output: α and β of the node (α_{avg}, β_{avg})

1: **declare** a database table *table_ref* to store the data of reference tags

2: **declare** columns TagID, RSSI, Location, Distance for *table_ref*

3: **declare** columns temp_1 and temp_2 for *table_ref*

4: **declare** variables α_{tl}, β_{tl}

5: **update** *table_ref* column Distance using the location of the reference tags and node

6: **compute** a trendline using the logarithm of distance and RSSI value in *table_ref*

7: **store** the slope in α_{avg} and y-intercept in β_{avg}

8: **output** $\alpha_{avg}, \beta_{avg}$

4.1.1.3. Looping Algorithm

The Looping Approach is based on the Averaging Approach and the Trendline Approach. In the previous two approaches, all of the reference tags will be counted in computing the corresponding α and β values. However, some reference tags may not provide beneficial information for calibration. Thus, those reference tags should not be counted. Fig. 19 shows the flow of the Looping Approach. To make the decision not to count a reference tag, in the Looping Approach the α and β values are first computed using all reference tags, such that we have α_0 and β_0. As the actual distances between the reference tags and the nodes can be calculated, α_0 and β_0 can be used to estimate the distance of the reference tags. The estimation error of each reference tag can then be sorted out, and the decision made on whether a particular reference tag should be excluded. Thus,

$$RSSI_i = \alpha_0 \log_{10} d_{ie} + \beta_0 \tag{27}$$

$$error_i = d_{ia} - d_{ie} \tag{28}$$

where $RSSI_i$, d_{ia}, d_{ie}, and $error_i$ denote the RSSI value, actual distance, estimated distance, and distance error for tag i, respectively. Note that $i = (1, 2, 3 \dots n)$

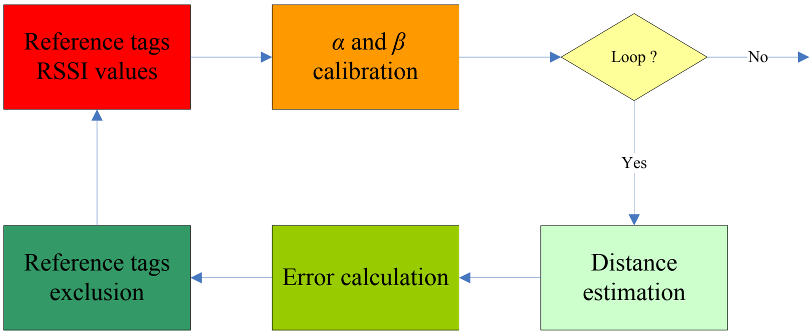


Fig. 19 Flow of the Looping Approach

According to the value of $error_i^2$, the reference tag with greatest error can be sorted out and excluded in the next loop. In the first loop, the new values of α and β can be computed by repeating the estimation by selecting other reference tags. By repeating the above steps, at most *n-2* loops can be performed such that *n-2* sets of α and β values can be obtained. A comparison of the results using different approaches will be given in Chapter five. The detail steps of algorithm are shown in Algorithm 3.

Algorithm 3: algorithm for calibrating α and β for estimating the distance using Looping Algorithm based on Averaging Algorithm or Trendline Algorithm

Input: locations of nodes

locations of *n* Reference tags $(R_1, R_2, \ldots, R_n)$

RSSI values of reference tags

minimum loop number

accepted error

Output: α and β of the node $(\alpha_{loop}, \beta_{loop})$

declare a database table *table_ref* to store the data of reference tags

declare columns TagID, RSSI, Location, Distance, Estimated Distance, Error, and Error^2 for *table_ref*

declare columns temp_1 and temp_2 for *table_ref*

declare variables α_{loop}, β_{loop}

for less than minimum loop number or error less than accepted error **do**

  run Algorithm 1 or Algorithm 2

  store output in α_{loop}, β_{loop}

  for each tag in *table_ref* do

    compute the Estimated Distance using α_{loop}, β_{loop}

    compute the Error by subtracting Distance with Estimated Distance

    compute the Error^2

  end for

  sort *table_ref* in descending order of column Error^2

  delete first data record in *table_ref*

end for

output α_{loop}, β_{loop}

4.1.2. Location Estimation

4.1.2.1. Enlarge and Diminish Method (EDM)

While all distances are estimated, the location of the corresponding tracking tag can be also estimated using the concept of trilateration.

Consider that the tracking tag located at coordinate (h, k) is detected by three nodes located at (x_1, y_1), (x_2, y_2), and (x_3, y_3) with distances d_1, d_2, and d_3 respectively, such that we can have the simultaneous equation:

$$\begin{cases} (h - x_1)^2 + (k - y_1)^2 = (d_1)^2 \\ (h - x_2)^2 + (k - y_2)^2 = (d_2)^2 \\ (h - x_3)^2 + (k - y_3)^2 = (d_3)^2 \end{cases} \tag{29}$$

However, (29) is an ideal case that there is only one interception (h, k). Realistically, there are many different cases that have no interception or more than one interception. One method of checking the number of interception points is to compare the distances between nodes with the sum of the corresponding estimated distances d_1, d_2, and d_3. For example,

$$(d_1 + d_2) - \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{30}$$

If the result of (30) is greater than zero, there should be two interceptions. If the result of (30) is equal to zero, there should be only one interception. There should be no interception if the result of (30) is less than zero. Some cases of no interception were found during the testing and an example is shown in Fig. 20. Besides those cases, there may be some cases that have not yet been discovered. To simplify the process of location estimation, the Enlarge and Diminish Method (EDM) is proposed. In essence, EDM is a method that enlarges or diminishes the value of d_1, d_2, and d_3. This method will first be employed to choose the maximum d_{max} and minimum d_{min} from d_1, d_2, and d_3, hence to enlarge or diminish them according to the ratio of d_{max} and d_{min} such that the corresponding distance between the nodes is equal to the sum of d'_{max} and d'_{min}. The aim is to make the largest circle intercept with the smallest one. While the largest circle intercepts with the smallest one, the third circle must intercept with either circle. For the result of EDM, please refer to Fig. 20.

Assume $d_{max} = d_1$ and $d_{min} = d_3$, such that

$$(d_1 + d_3) - \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} < 0 \tag{31}$$

According to EDM, $d'_1 : d'_2 : d'_2 = d_1 : d_2 : d_2$ and note that $d'_{max} = d'_1$ and $d'_{min} = d'_3$, thus:

$$\begin{cases} (d'_1 + d'_3) = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} \\ d'_3 = \dfrac{d_3}{d_1} d'_1 \end{cases} \tag{32}$$

By solving (32), we can obtain:

$$d_1' = \left(\sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2}\right)\left(\frac{d_1}{d_1 + d_3}\right) \tag{33}$$

And

$$d_2' = \frac{d_2}{d_1} d_1' = \frac{d_2}{d_3} d_3' \tag{34}$$

$$d_3' = \frac{d_3}{d_1} d_1' = \frac{d_3}{d_2} d_2' \tag{35}$$

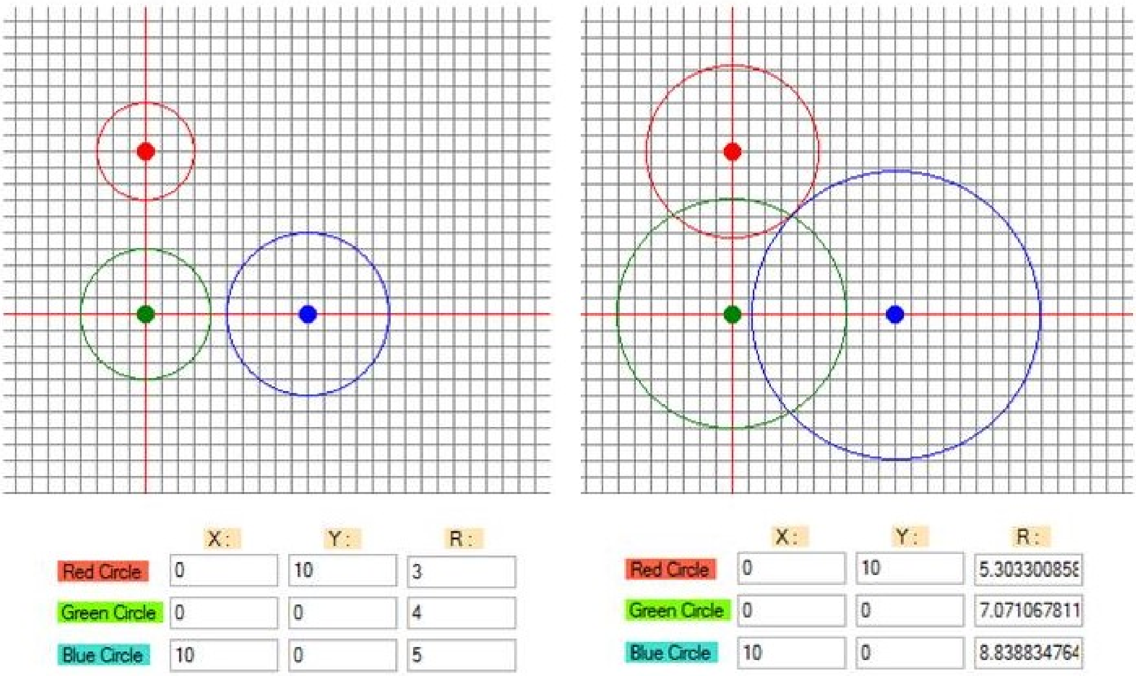


Fig. 20 Example of no interception and result of EDM

4.1.2.2. Least Square Distance Error (LSDE)

Least Error Square (LES) [43] is a common algorithm used for solution approximation. Least Square Distance Error (LSDE) is an algorithm based on LES. Firstly, for each coordinates (x, y) inside the tracking area, the distances $d_{j\,(x,y)}$ from each node *j* can be obtained. After all distances between the tracking tag *k* and all nodes are estimated (i.e. $d_{k1}, d_{k2}, \dots, d_{km}$), the distance error square of coordinate (x, y) for node *j* can be obtained by:

$$e_{j\,(x,y)}^{2} = \left(d_{j\,(x,y)} - d_{kj}\right)^{2} \tag{36}$$

Next, we can compute the sum of the error square for all nodes at coordinate (x, y) by:

$$e_{sum\,(x,y)} = \sum_{j=1}^{m} e_{j\,(x,y)}^{2} \tag{37}$$

Finally, the coordinate (x, y) with the least of the error $e_{sum\,(x,y)}$ will be selected as the estimated location of the tracking tag *k*.

4.1.2.3. Least Square Ratio Error (LSRE)

Least Ratio Error Square (LSRE) is another algorithm based on LES. Different from LSDE, LSRE is an algorithm which selects the coordinate according to the least square error of ratio instead of distance. To compute the ratio, two nodes *p* and *q* will be considered at each time such that:

$$e_{pq\,(x,y)}^2 = \left(\frac{d_{p\,(x,y)}}{d_{q\,(x,y)}} - \frac{d_{kp}}{d_{kq}}\right)^2 \tag{38}$$

And the sum of the error square of coordinate (x, y) will be computed by:

$$e_{sum\,(x,y)} = \sum_{p=1}^{m} \sum_{q=1,q\neq p}^{m} e_{pq\,(x,y)}^2 \tag{39}$$

By sorting $e_{sum\,(x,y)}$ for all coordinates (x, y), the least $e_{sum\,(x,y)}$ can be found and the corresponding coordinate will be the estimation result.

4.1.2.4. 2-D Bisection

LSDE and LSRE are introduced previously. However, the progress is not efficient for checking every coordinates in the tracking area. Thus, Bisection method is proposed to improve LSDE and LSRE. Bisection method is used to compute an approximate root of a function when calculation and graphical method are not available or too complex. It improves the converging methods rapidly to get a rough approximation to the solution. [44] In the proposed location tracking system, Bisection could be apply to both x-coordinate and y-coordinate, so it is named 2-D Bisection.

For a quadrilateral on a coordinate system with four known vertexes shown in Fig. 21, it could be divided into four sub-quadrilateral by the mid-point of its height and width which shown in Fig. 22. By using 2-D Bisection, the estimated region will be reduced into one-fourth of the original.

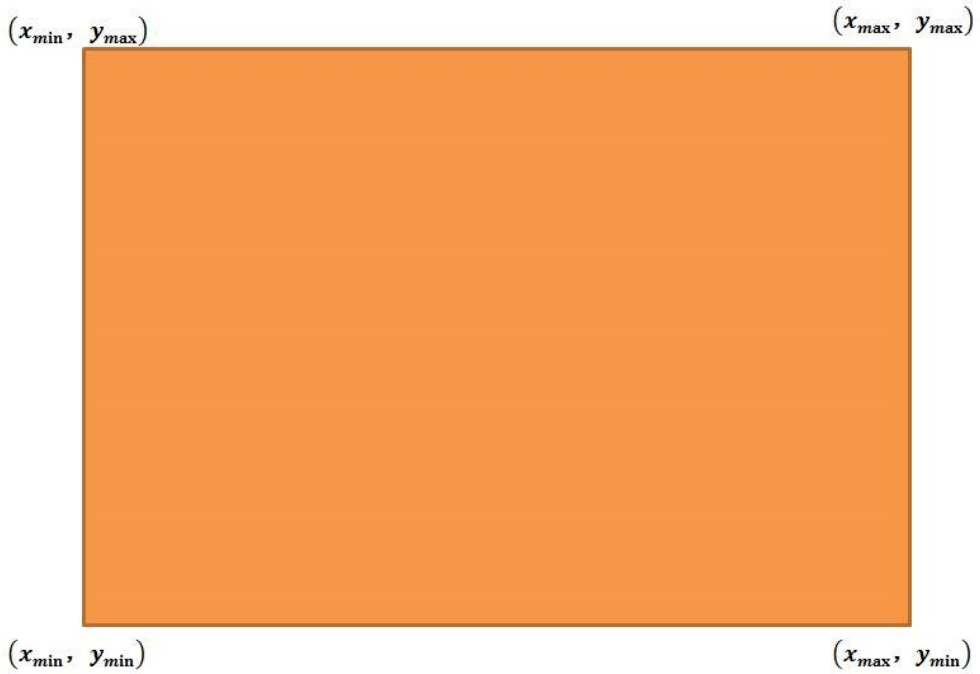


Fig. 21 2-D Bisection

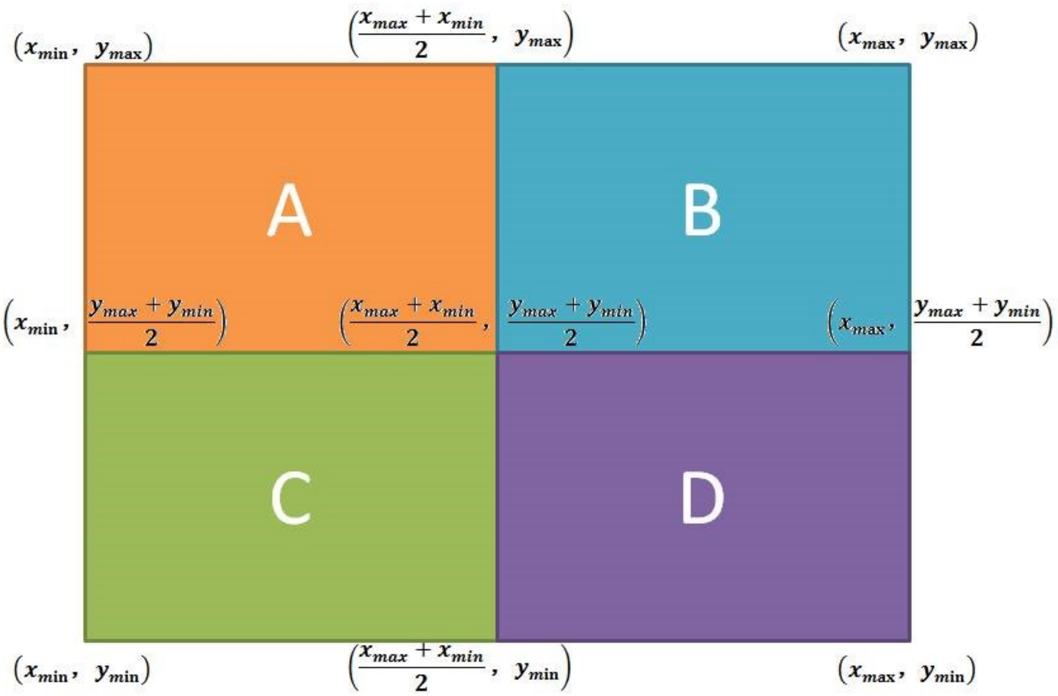


Fig. 22 2-D Bisection result

In the system calculation, the centre of each region is used to represent the region itself. During the *i*-th loop, a region bounded with coordinates (x_{min}, y_{max}), (x_{max}, y_{max}), (x_{min}, y_{min}), and (x_{max}, y_{min}) will be divided into four sub-regions A_i, B_i, C_i, and D_i. Secondly, the centres of each regions C_{Ai}, C_{Bi}, C_{Ci} and C_{Di} will be computed. Next, distances between the centres and nodes can be calculated. By subtracting the result will the estimated distance respectively, the error of each region e_a, e_b, e_c, and e_d can be computed. After that, one of the regions with the least error square ${e_a}^2$, ${e_b}^2$, ${e_c}^2$, and ${e_d}^2$ will then be sorted out. By repeating above process until specific loops or the error becomes less than a target, the estimated location can be represented by the centre of that region. To compute the errors, there are two algorithms outlined in pervious section which are LSDE and LSRE. The details of the 2-D Bisection algorithm using LSDE or LSRE are shown below:

Algorithm 4: algorithm for estimating the location of tracking tag using 2-D Bisection with LSDR or LSRE

Input: area range $(x_{max}, x_{min}, y_{max}, y_{min})$

estimated distances (d_1, d_2, d_3)

locations of nodes (P_1, P_2, P_3)

minimum loop number

accepted error

Output: estimated location (x_{est}, y_{est})

declare variables $e_a,\ e_b,\ e_c,\ e_d,\ x_e,\ y_e$

calculate three ratio r_{12}, r_{13}, r_{23} by d_1, d_2, d_3

for less than minimum loop number or error less than accepted error **do**

    divide the region into 4 sub-region $A_i,\ B_i,\ C_i$, and D_i

    compute the centers of sub-region $C_{Ai},\ C_{Bi},\ C_{Ci}$ and C_{Di}

    for each center of region **do**

        calculate the distance between each center ($C_{Ai},\ C_{Bi},\ C_{Ci}$ and C_{Di}) and each note (P_1, P_2, P_3)

        compute the error according LSDE or LSRE

        store the error in $e_a,\ e_b,\ e_c,\ e_d$

    end for

    if ${e_\mathrm{a}}^2$ is the smaller than ${e_\mathrm{b}}^2,\ {e_c}^2$, and ${e_d}^2$ **then**

        store coordinate of $C_{\mathrm{A}i}$ in $x_{est},\ y_{est}$

        replace area range by $x_{\min}, (x_{max} + x_{min})/2\,, y_{max}, (y_{max} + y_{min})/2$

end if

if $e_b{}^2$ is the smaller than $e_a{}^2$, $e_c{}^2$, and $e_d{}^2$ **then**

store coordinate of C_{Bi} in x_{est}, y_{est}

replace area range by $(x_{max} + x_{min})/2$, x_{max}, y_{max}, $(y_{max} + y_{min})/2$

end if

if $e_c{}^2$ is the smaller than $e_a{}^2$, $e_b{}^2$, and $e_d{}^2$ **then**

store coordinate of C_{Ci} in x_{est}, y_{est}

replace area range by x_{min}, $(x_{max} + x_{min})/2$, $(y_{max} + y_{min})/2$, y_{min}

end if

if $e_d{}^2$ is the smaller than $e_a{}^2$, $e_b{}^2$, and $e_c{}^2$ **then**

store coordinate of C_{Di} in x_{est}, y_{est}

replace area range by $(x_{max} + x_{min})/2$, x_{max}, $(y_{max} + y_{min})/2$, y_{min})

end if

end for

output x_{est}, y_{est}

Chapter 5. EXPERIMENT AND EVALUATION

To evaluate the position estimation algorithms, many experiments have been conducted based on the system prototype. In this section, some representative results are presented to discuss the major findings. The experiments were conducted in a semi-open area using approaches similar to experiments conducted in the previous literature. Unless otherwise specified, there are nine reference tags and three nodes. The aim of the experiments is to verify the functionalities of the protocol, compare the performance of the position estimation methods: Averaging, Averaging with EDM, Trendline, Trendline with EDM, Averaging with LSDE, Averaging with LSRE, Trendline with LSDE, and Trendline with LSRE and conduct further analysis on the best method.

Distance estimation has been the first consideration since location cannot be estimated with distance information. So, distance estimation algorithms have been proposed firstly. After testing the algorithms with the trilateration, EDM is needed to improve the location estimation and first experiment is conducted to evaluate the performance of distance estimation algorithms and EDM in an area measuring three meters by three meters.

However, the results of second experiment using those algorithms are not satisfied in a larger area which is nearly eight meters by four meters. Thus, LSDE, LSRE, and 2D-bisection are proposed. In this chapter, two experiment results mentioned in above will be presented.

5.1. First experiment setup

Three distance estimation algorithms using the reference tag method were proposed in the last chapter. To study the performance of the proposed algorithms, testing was conducted in an indoor environment as shown in Fig. 23. In the testing process, nine reference tags and three nodes were used and placed in an area measuring three meters by three meters. Details of the placement are presented in Fig. 24.

Fig. 23 Environment of first experiment

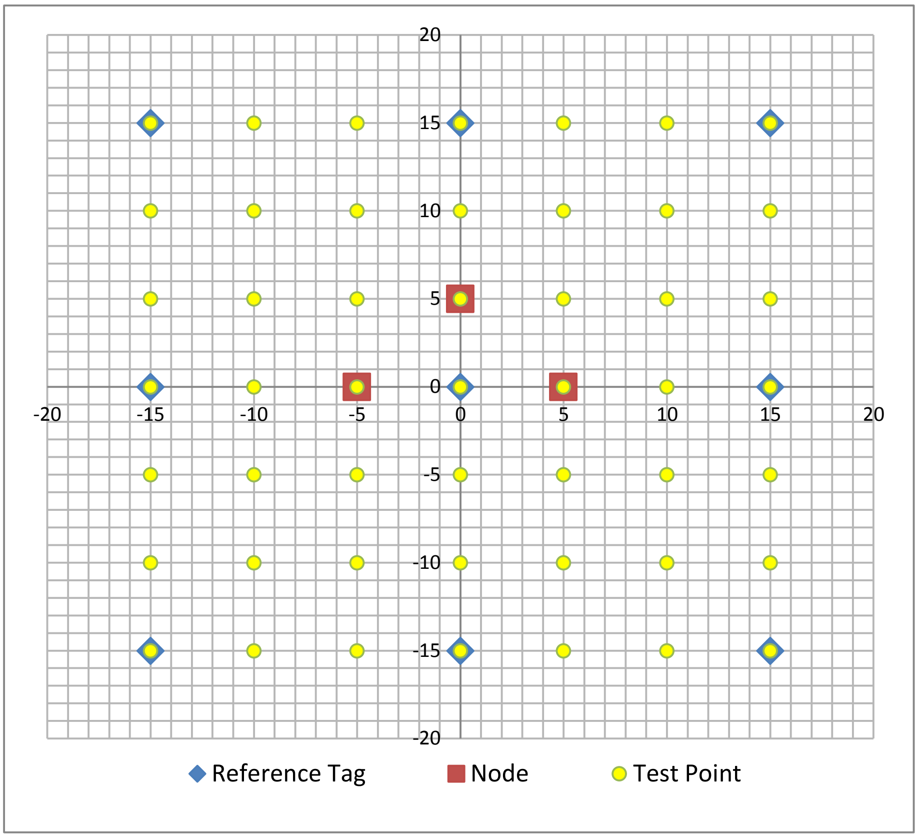


Fig. 24 Placement of first experiment

5.2. Second experiment setup

Similar tests are conducted in a larger area with different environment conditions. Fig. 25 shows a testing environment of second experiment. During the test, there are also nine reference tags and three nodes which are same as pervious test.

Fig. 25 Environment of second experiment

5.3. Result analysis

Many test cases have been conducted to verify the functions of the system and the aforementioned protocols. The tests confirmed the correct operation of the system. Figure 26 shows the system interface of one of the test cases. We have also conducted many tests to evaluate the RSSI distributions. Fig. 27, 28 and 29 which show the RSSI values at different positions during the first testing while Fig. 30, 31 and 32 which show the RSSI values at different positions during the second testing.

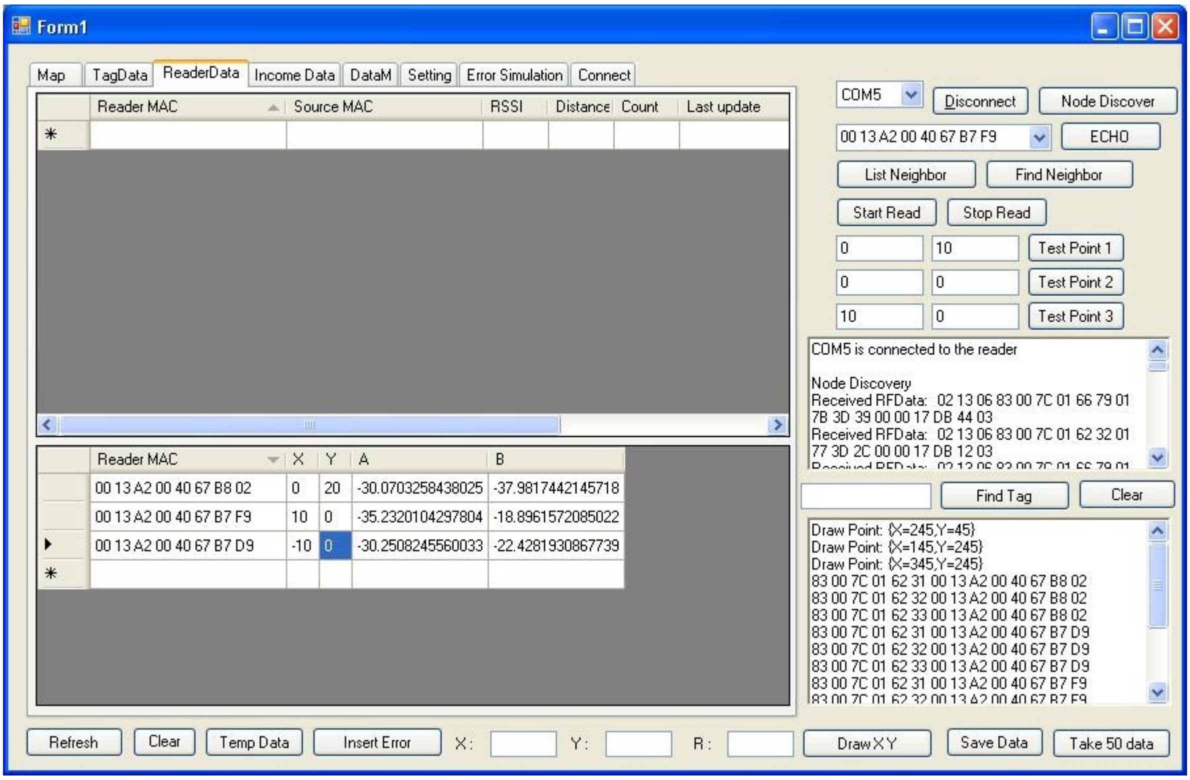


Fig. 26 User interface of the prototype system for testing basic system functions

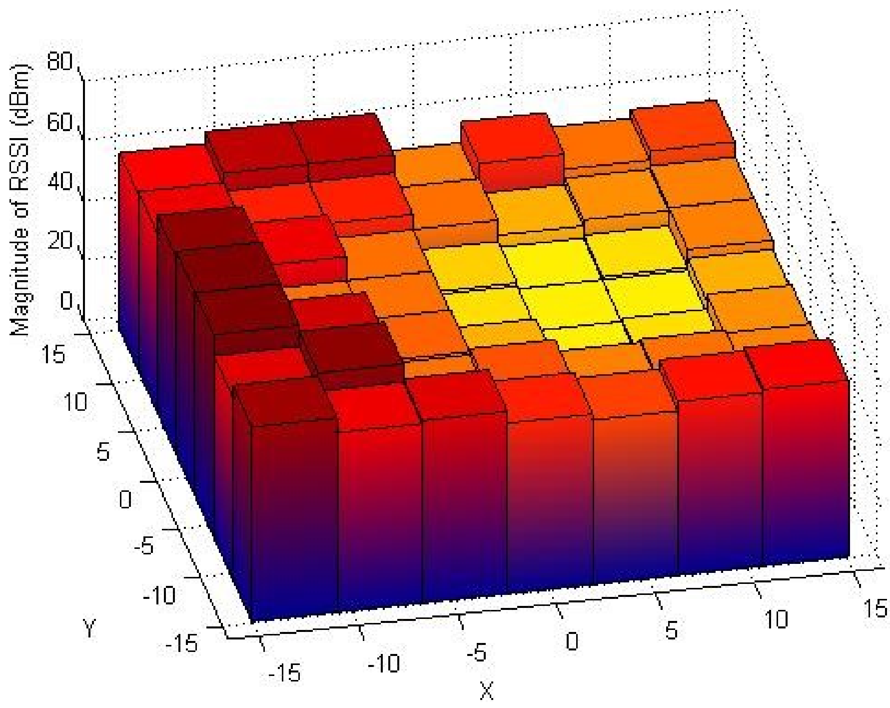


Fig. 27 RSSI perceived by the node at (5,0)

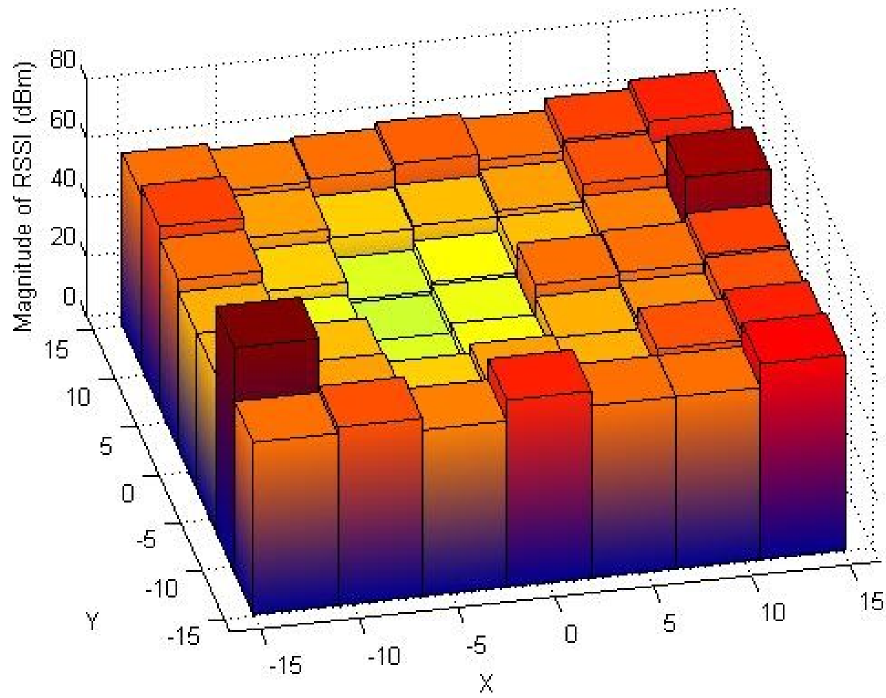


Fig. 28 RSSI perceived by the node at (-5,0)

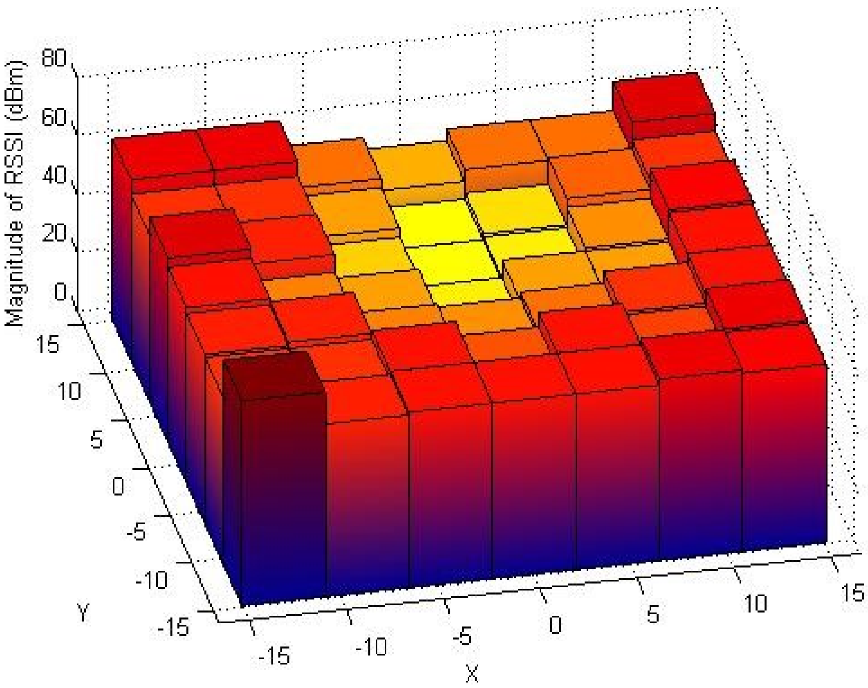


Fig. 29 RSSI perceived by the node at (0,5)

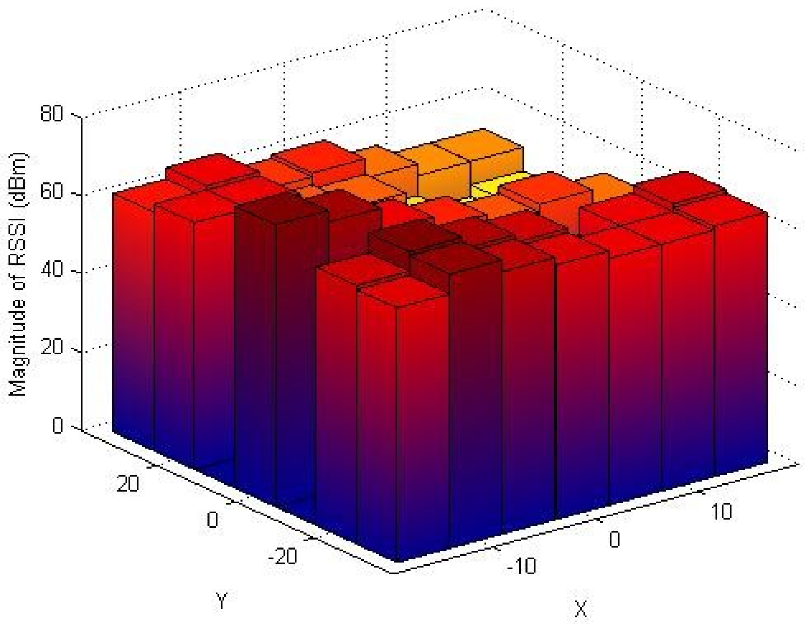


Fig. 30 RSSI perceived by the node at (12,24)

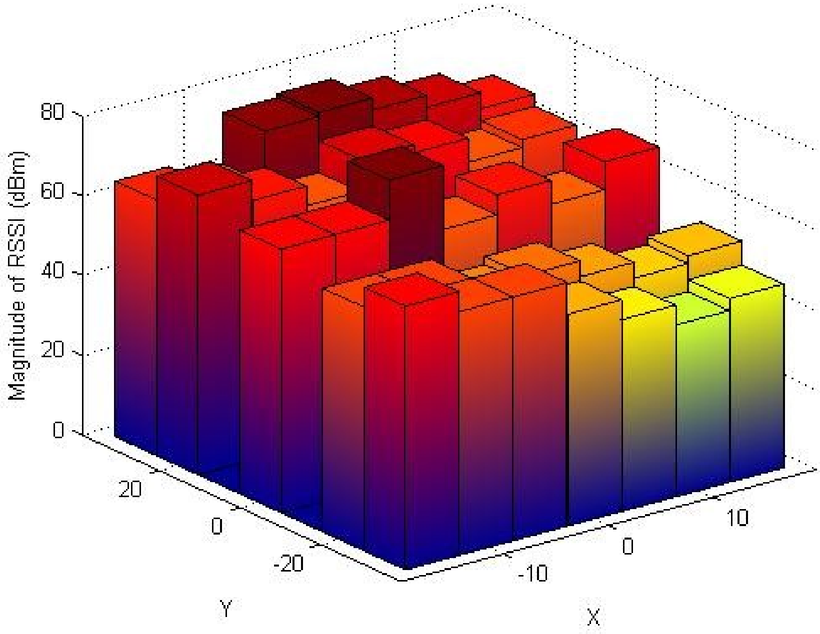


Fig. 31 RSSI perceived by the node at (12,-30)

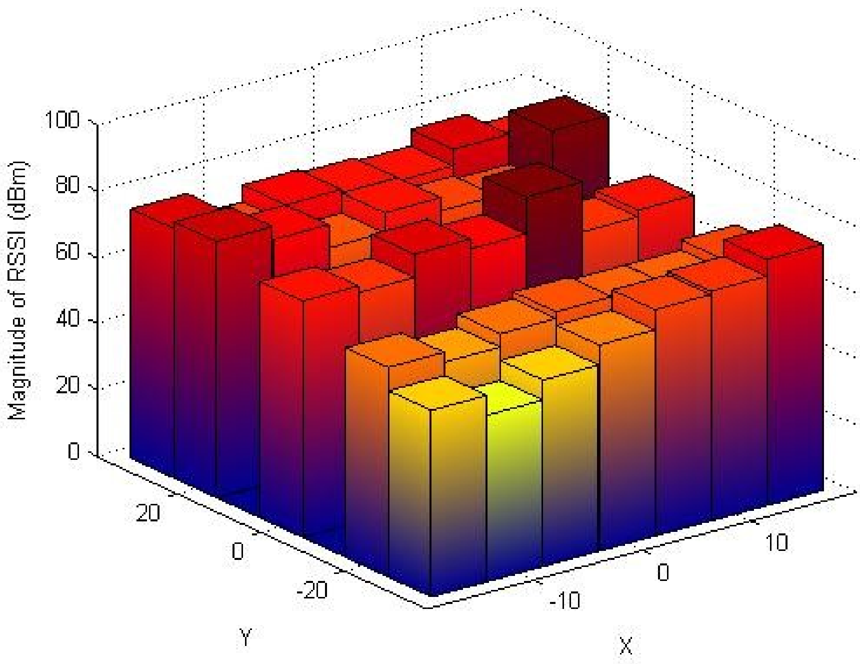


Fig. 32 RSSI perceived by the node at (-12,-30)

It shows that, depending on the case, the RSSI values can have different variations. For example, there can be greater variations in the middle or at the edges of the area. After testing the system operations, we conducted experiments to compare the performance of the aforementioned position estimation algorithms.

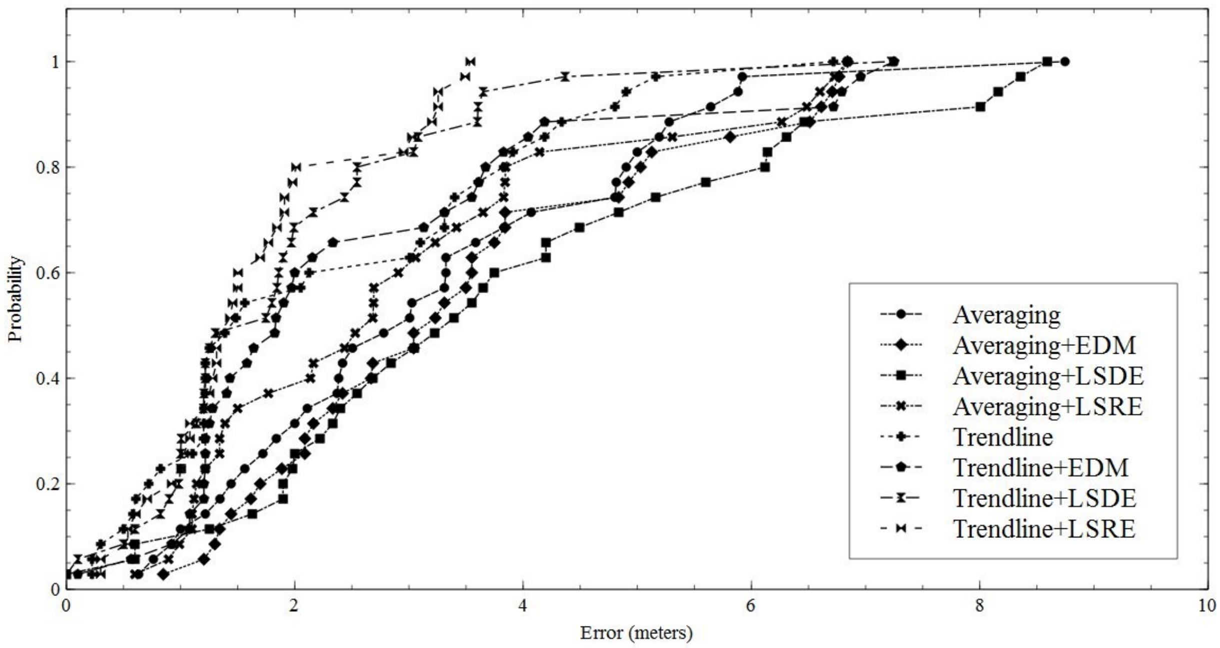


Fig. 33 Comparison of the different position estimation algorithms

Figure 12 shows the CDF of errors for the different position estimation algorithms. It shows that, in general, the trendline approach can perform better than the averaging approach.

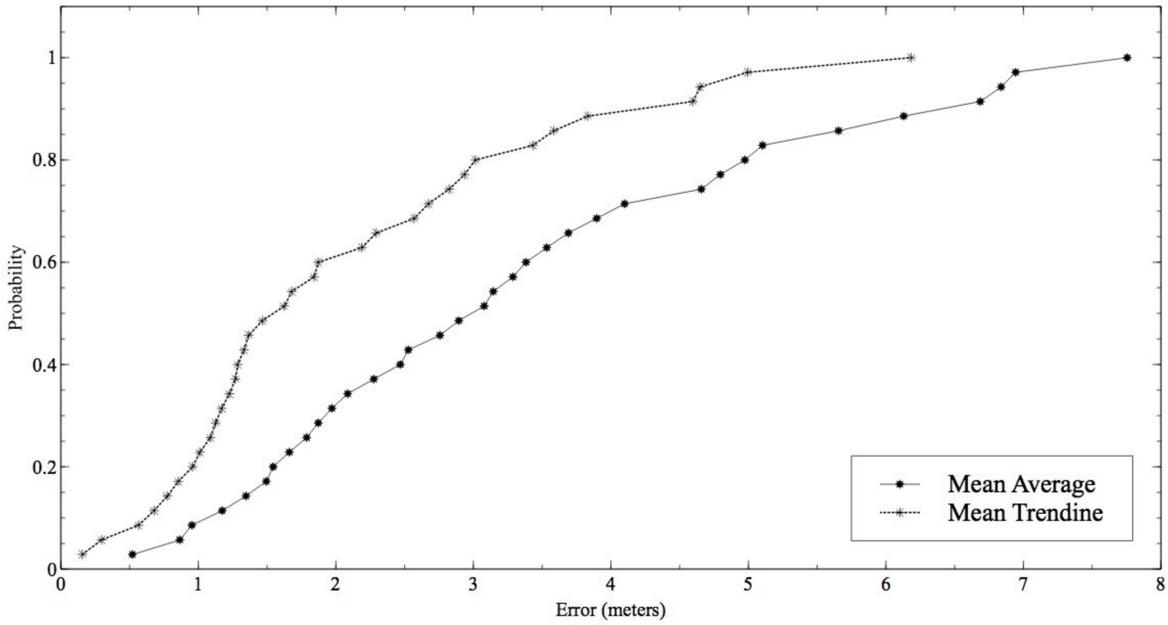


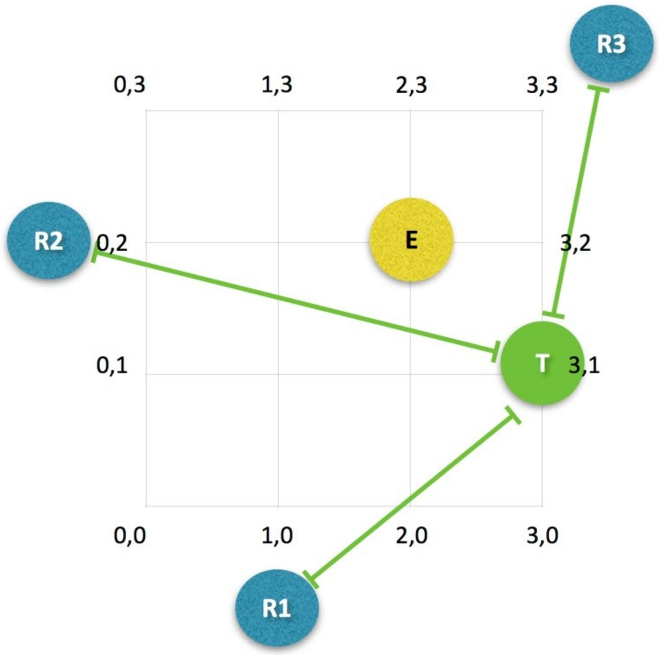
Fig. 34 Comparison of the averaging and trendline approaches

	Mean Average	**Mean Trendline**
25th percentile	1.788	1.088
50th percentile	3.079	1.625
75th percentile	4.658	2.824
100th percentile	7.755	6.183

Fig. 35 Comparison of the averaging and trendline approaches using Mean value

Fig. 34 and 35 give a clearer picture by computing the mean values of the trendline methods as well as the averaging methods. For example, it shows that 50% of the tags can be detected within an error of 1.6 m for the trendline methods as compared to 3.1

m for the averaging methods (i.e., a difference of about 100%). Among all of the methods, it can be seen from Fig. 33 that Trendline with LSRE provides the best performance. Hence, we shall focus on studying this method in the subsequent analysis. In general, it is found that LSRE can outperform LSDE. Under ideal conditions, both LSRE and LSDE give the same result (i.e., the intersection of the three circles by means of trilateration). However, in practice the active RFID tags may not give a constant signal strength. Indeed, from the experiments, it was found that the signal strength of a tag may be reduced or distorted by a certain percentage due to environmental effects and/or noise. As the readers receive the same signal from the tag, they get a similar effect (i.e., the received signal strength is reduced by a certain percentage). As a result, LSRE can give a better performance. Let us use a simplified example to explain this finding more clearly.



Reader	x	y
R1	1	-1
R2	-1	2
R3	4	4

Point (x,y)	LSDE	LSRE without/ with 20% RSSI reduction	LSDE with 20% RSSI reduction
1 (0,0)	3.43	2.88	3.41
2 (1,0)	2.90	4.12	2.81
3 (2,0)	2.00	2.32	2.14
4 (3,0)	1.18	0.91	1.98
5 (0,1)	3.33	1.39	3.11
6 (1,1)	2.33	1.06	2.03
7 (2,1)	1.21	0.50	1.08
8 (3,1)	0.00	0.00	1.18
9 (0,2)	3.40	1.18	3.14
10 (1,2)	2.18	0.80	1.84
11 (2,2)	1.22	0.56	0.99
12 (3,2)	1.22	0.61	1.54
13 (0,3)	3.15	1.12	3.09
14 (1,3)	2.22	0.96	2.13
15 (2,3)	1.86	0.90	1.89
16 (3,3)	2.40	0.96	2.61

Fig. 36 Example to compare LSDE and LSRE

As shown in Fig. 36, under an ideal situation, both LSDE and LSRE can provide the correct position. However when the estimated distances are reduced or distorted by 20%, LSDE provides an incorrect position but LSRE can still provide the correct position.

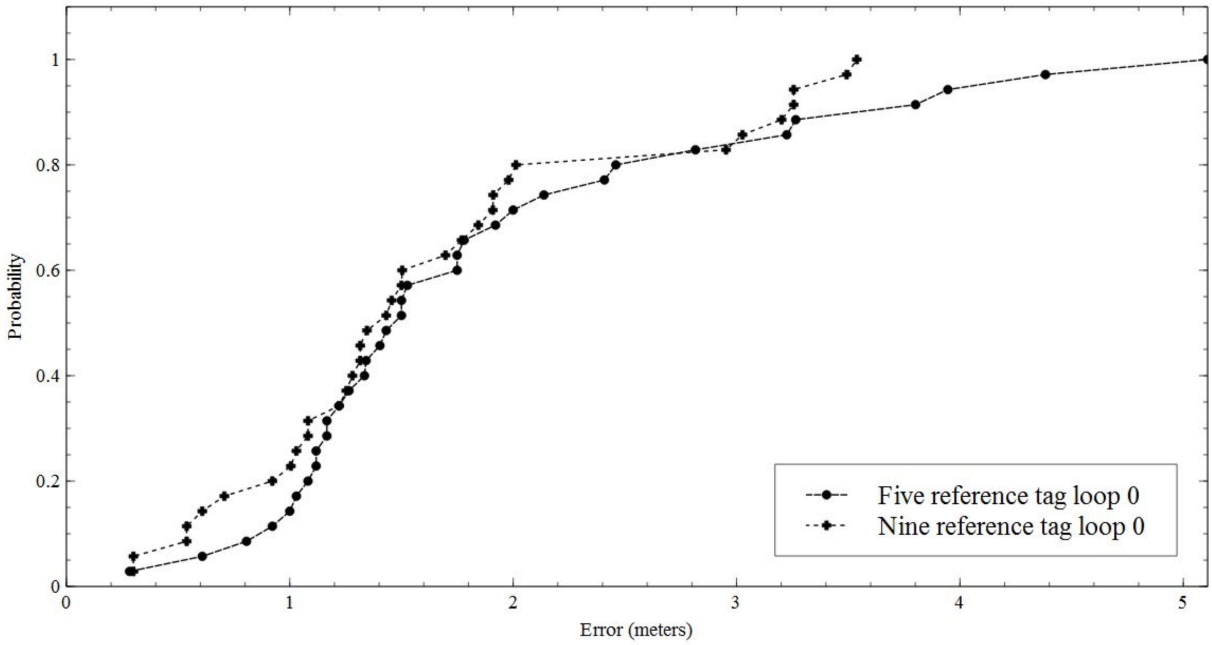


Fig. 37 CDF of error of nine and five reference tags using Trendline Algorithms with LSRE (a)

Fig. 37 shows the expected result, which is that by using nine reference tags rather than five reference tags, a better performance can be achieved. The figure also indicates that there are two effects or advantages of using more reference tags. First, the mean error can generally be reduced or there are more tags with fewer errors. Second, the largest error can also be reduced. Note that in our proposed system, the reference tags do not need to be placed according to a certain geometric or structural pattern. In other words, they can even be placed randomly (e.g., more reference tags can be placed in areas requiring a higher degree of calibration, such as areas affected by adverse environmental conditions). Of course, while it is better to place more reference tags for calibration purposes, there is also a cost issue (i.e., tradeoff).

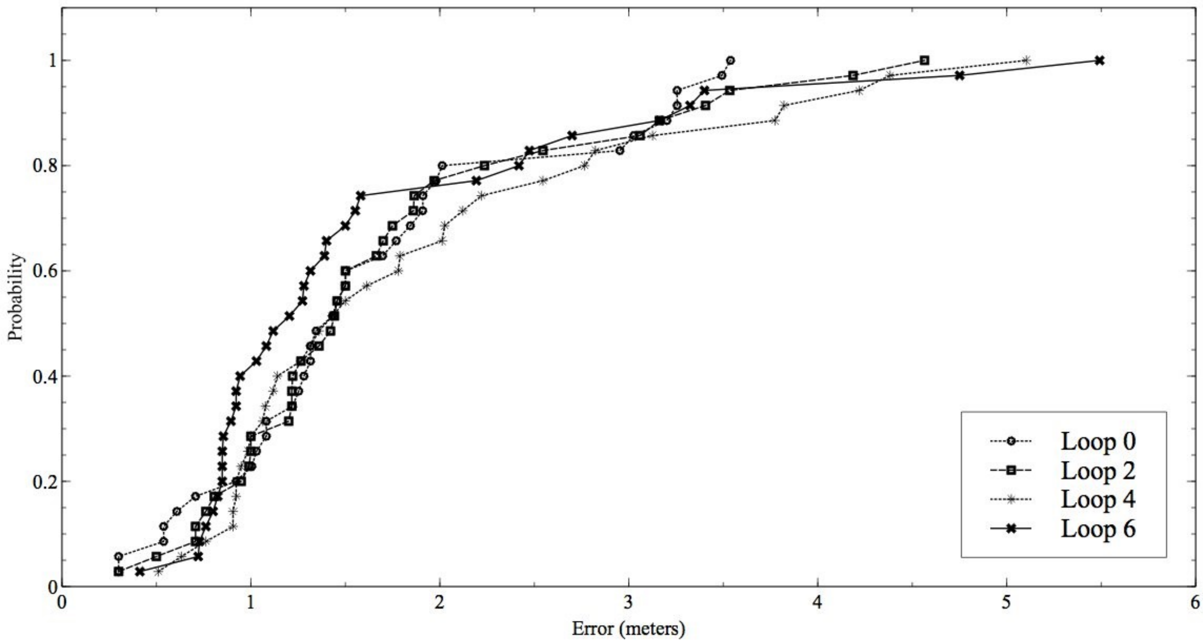


Fig. 38 CDF of error of Trendline Algorithms with LSRE and different loops

Fig. 38 shows the effect of looping. Note that, on the one hand, with more loops accuracy can be enhanced by eliminating the less accurate reference tags. However, on the other hand, there will be fewer reference tags for performing calibration, which also affects accuracy. Hence, there is a tradeoff, which depends on many factors. Therefore, in general it is difficult to determine the optimal number of loops. For example, in one of the cases, Fig. 38 shows that with six loops (i.e., fewer reference tags), while the mean error can be slightly improved, the largest error also increases. In Fig. 38, it can be seen that if there are fewer reference tags, the largest error will also increase.

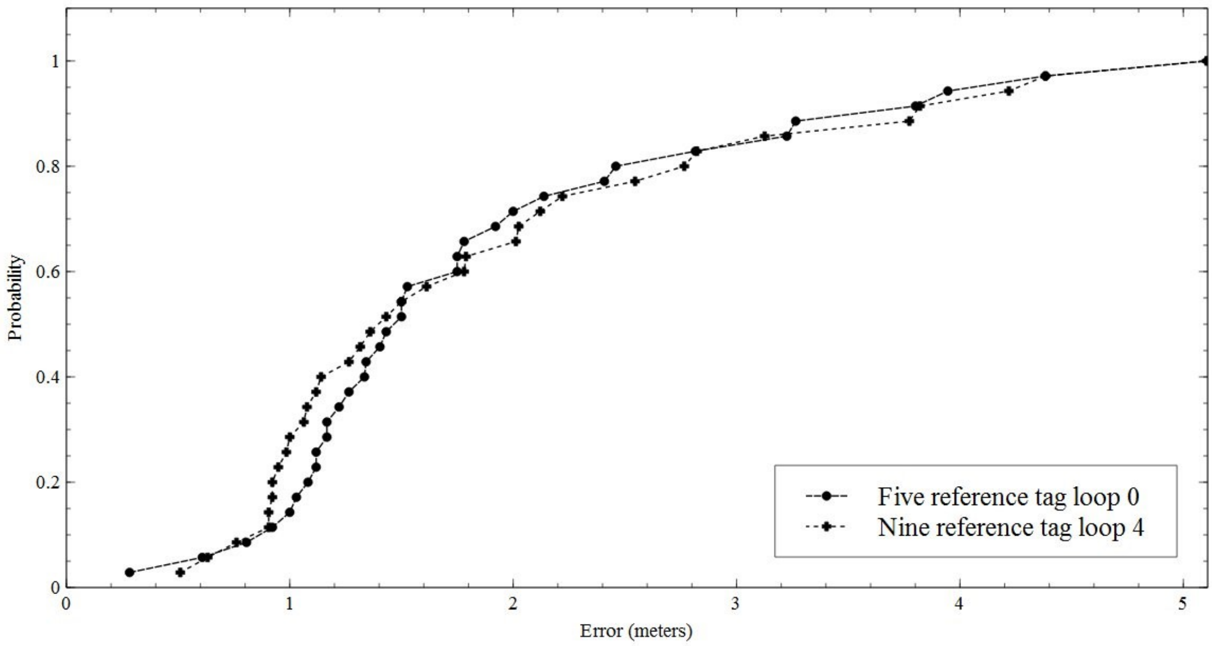


Fig. 39 CDF of error of same sampling size five

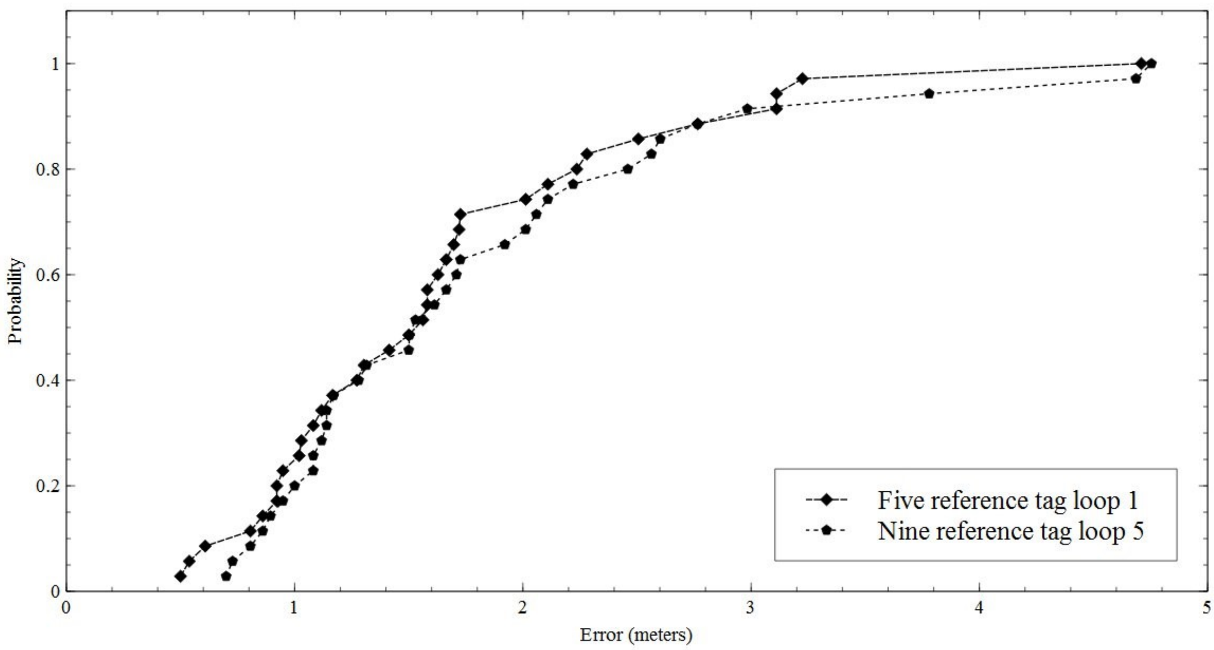


Fig. 40 CDF of error of same sampling size four

Fig. 39 shows the interesting result that the CDF of error for five reference tags with no loop is the same as that for nine reference tags with four tags because, in both cases, there are five reference tags. Fig. 40 shows another similar situation (i.e., they both have four reference tags).

Chapter 6. CONCLUSION AND FUTURE WORK

In conclusion, an active RFID-based position estimation system using a peer-to-peer network architecture has been presented. The proposed system makes use of active RFID technology for identifying and tracking people and objects. A P2P network with RFID readers is formed based on ZigBee. In other words, the readers communicate using the 2.4GHz ZigBee protocol. The P2P network can be formed using the command Node Discovery and Neighbour Discovery. The communications protocol can be used for the proposed system to transfer data and commands between tags, nodes, and the master. Using a P2P network architecture can greatly facilitate system setup and maintenance. We have also presented some position estimation algorithms for the RFID-based system. Experiments have also been conducted to study the algorithms. The Trendline with LSRE method was found to provide the best performance. To the best of our knowledge, while there are some works on using LSDE-related methods for RFID-based positioning systems, using LSRE is a relatively new approach. The results provide valuable insights into the design and performance of the RFID-based system.

For future work, it is of interest to consider using intelligent computing techniques (e.g., fuzzy logic) for positioning estimation purposes. While we have verified the basic operation of the P2P system through a working prototype, more work can also be conducted on different location-aware applications.

To enhance the system, studies still need to be conducted on how to improve the real case implementation, reliability, and on devising more accurate location estimation methods.

Appendices

A. More Figures of the experiment result and comparison

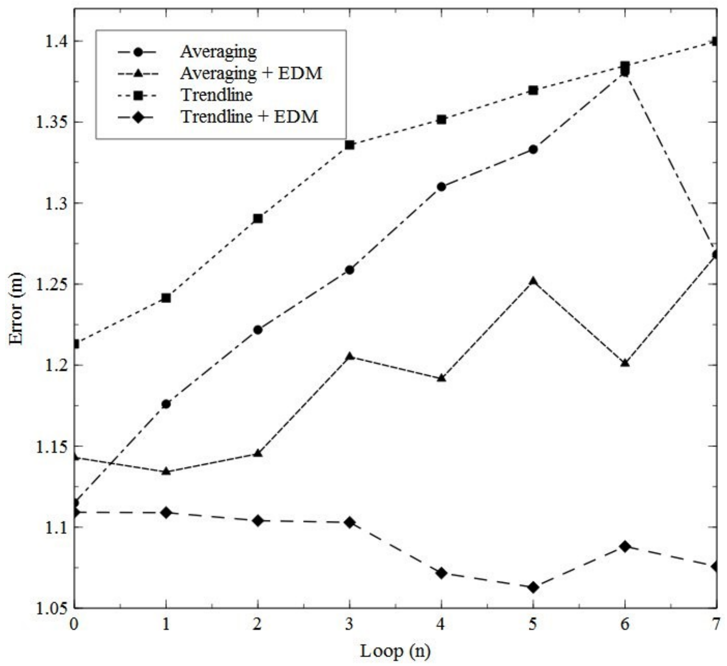


Fig. 41 Results of first experiment with nine reference tags

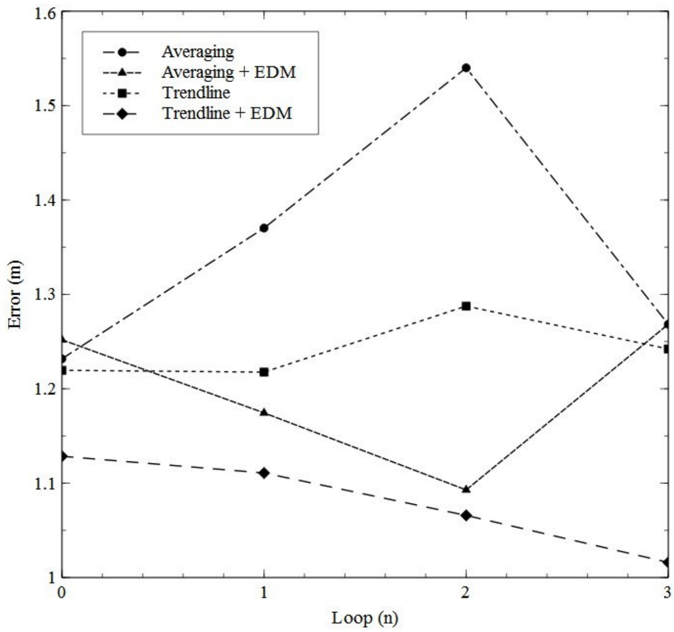


Fig. 42 Results of first experiment with five reference tags

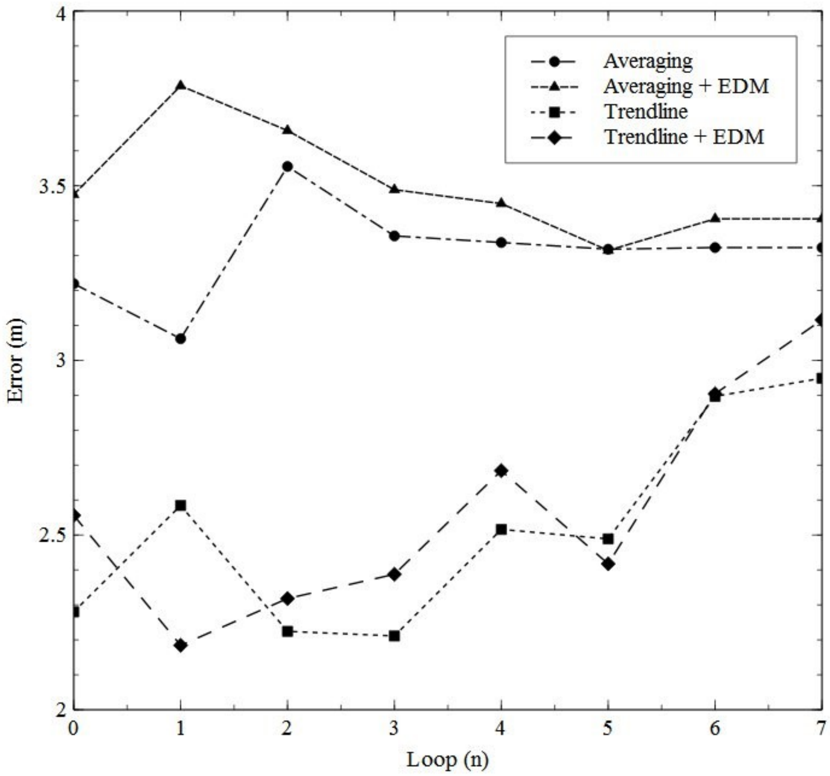


Fig. 43 Results of second experiment with nine reference tags

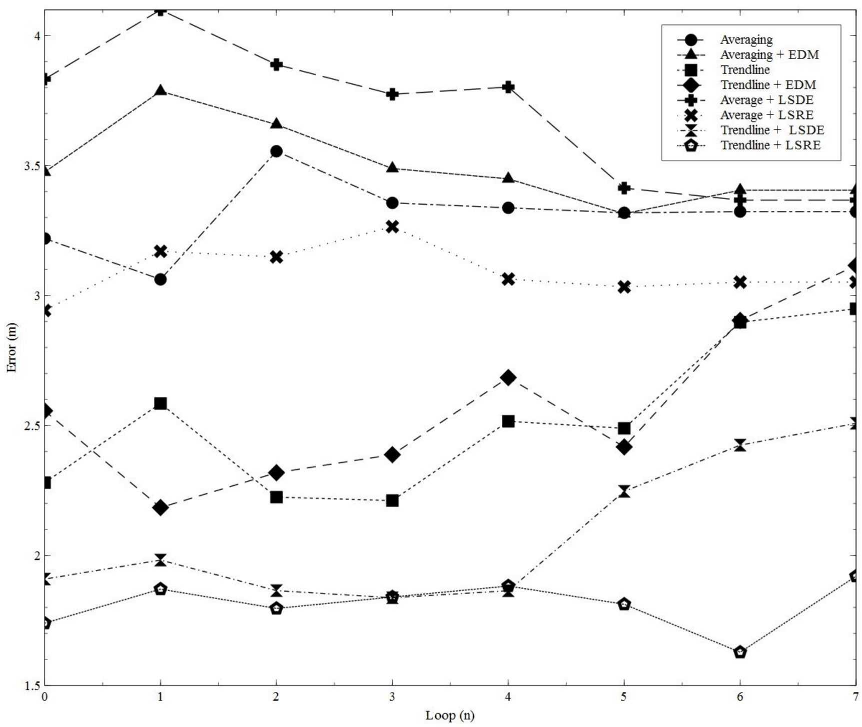


Fig. 44 Comparison of all proposed algorithms

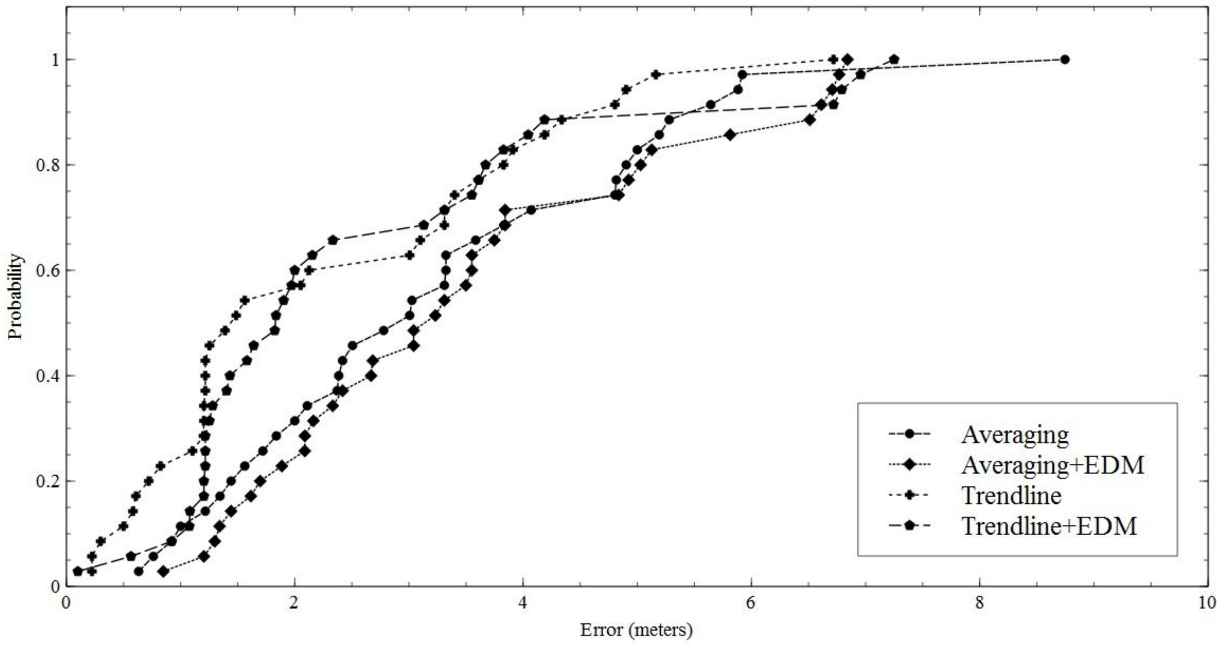


Fig. 45 CDF of error of second experiment

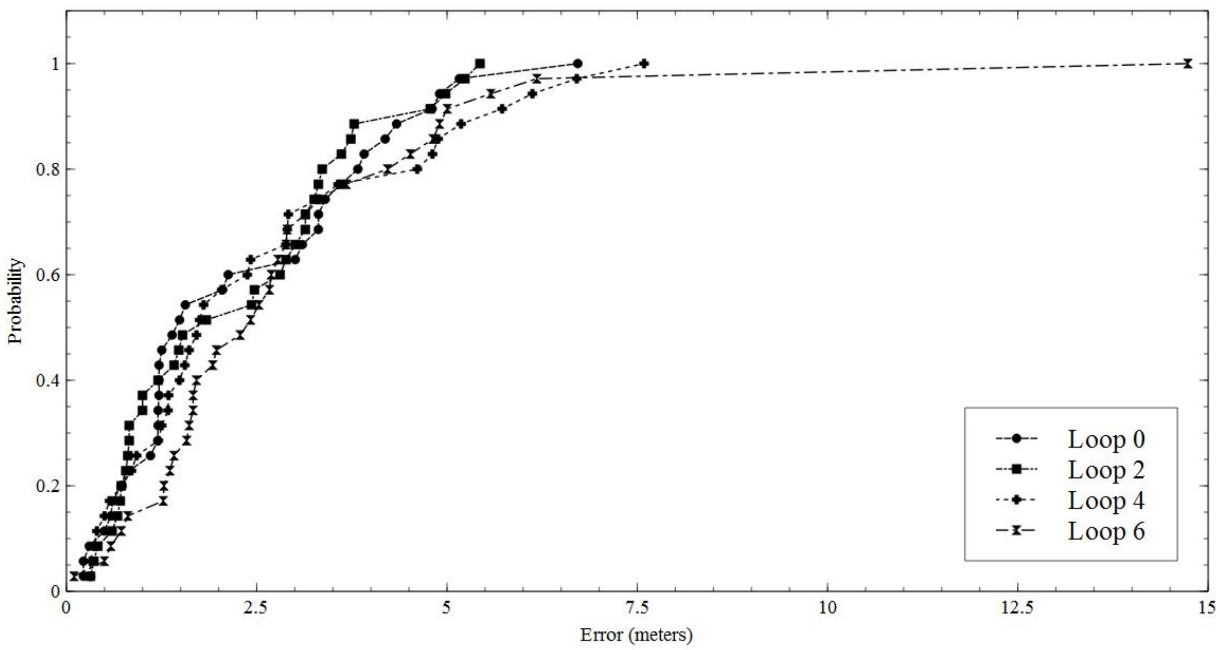


Fig. 46 CDF of error of Trendline Algorithm of different loops

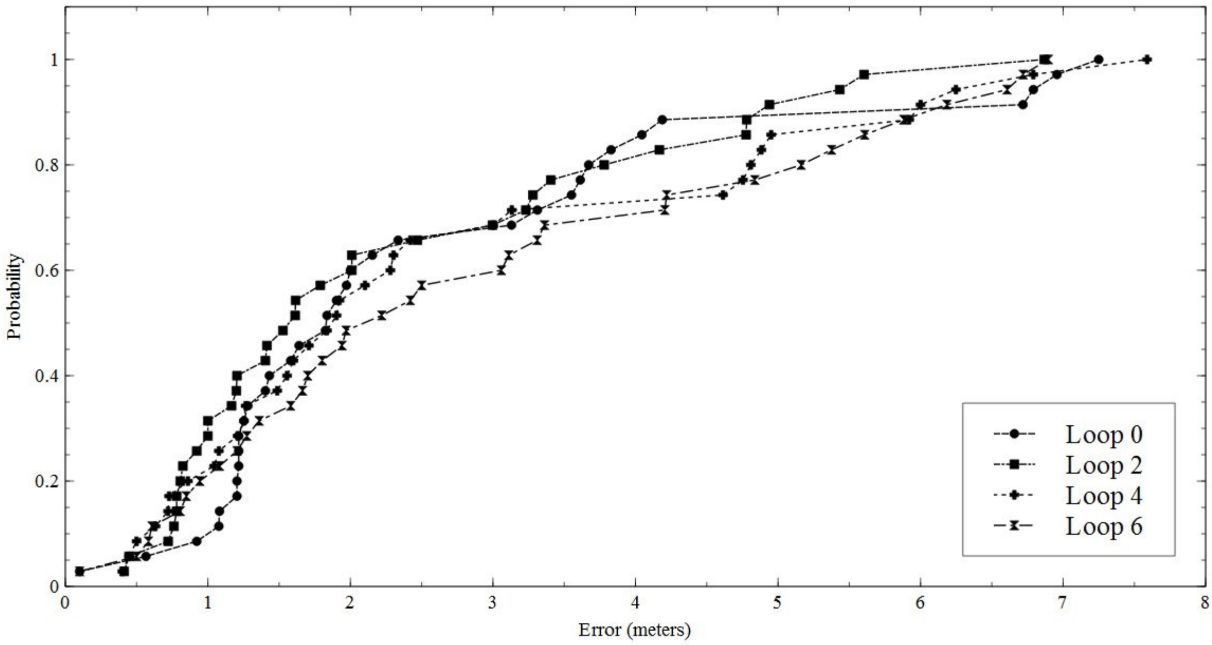


Fig. 47 CDF of error of Trendline Algorithm with EDM of different loops

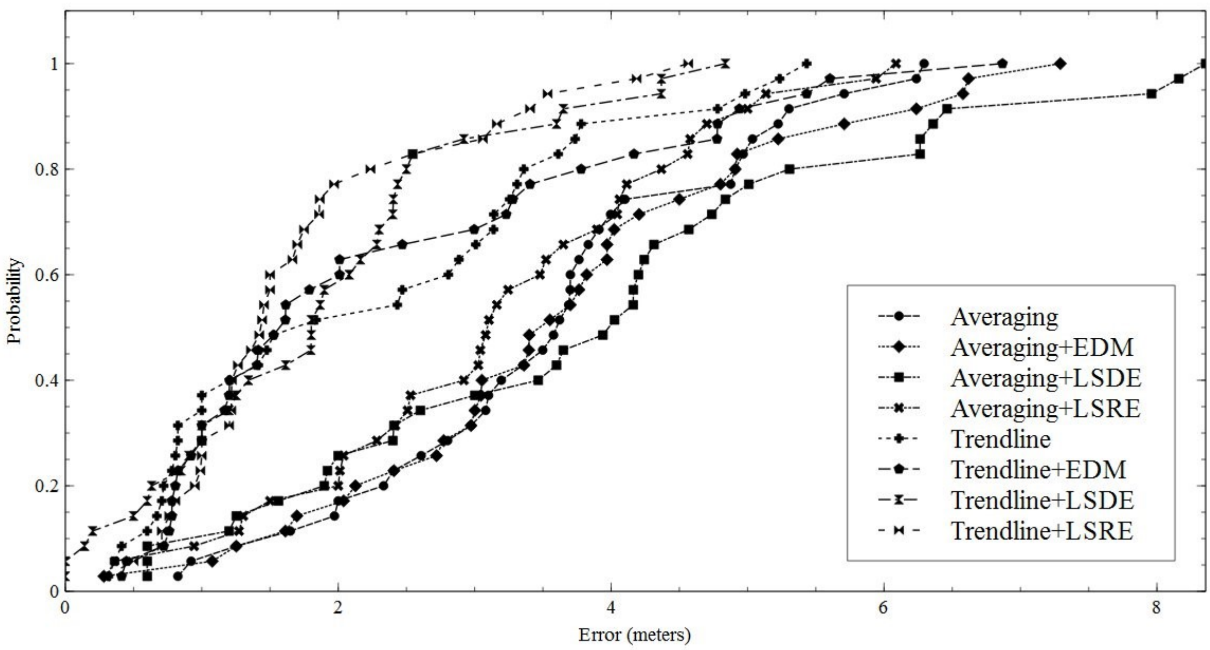


Fig. 48 CDF of error of nine reference tags with two loops

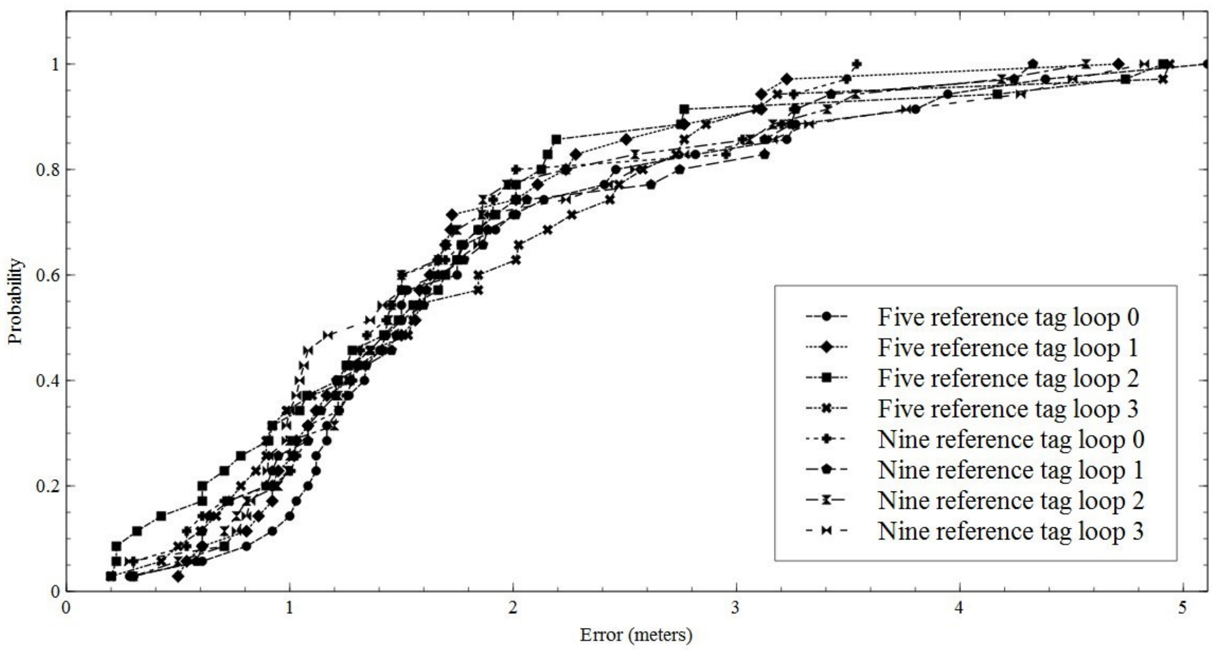


Fig. 49 CDF of error of Trendline Algorithms with LSRE and different loops

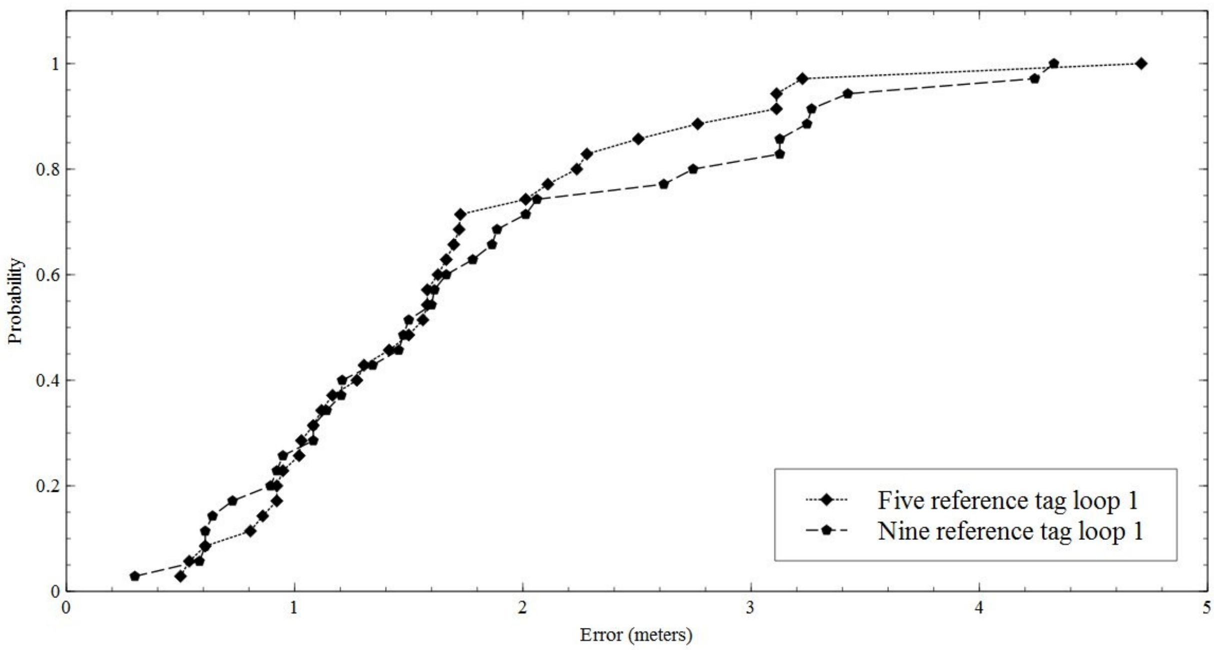


Fig. 50 CDF of error of nine and five reference tags using Trendline Algorithms with LSRE (b)

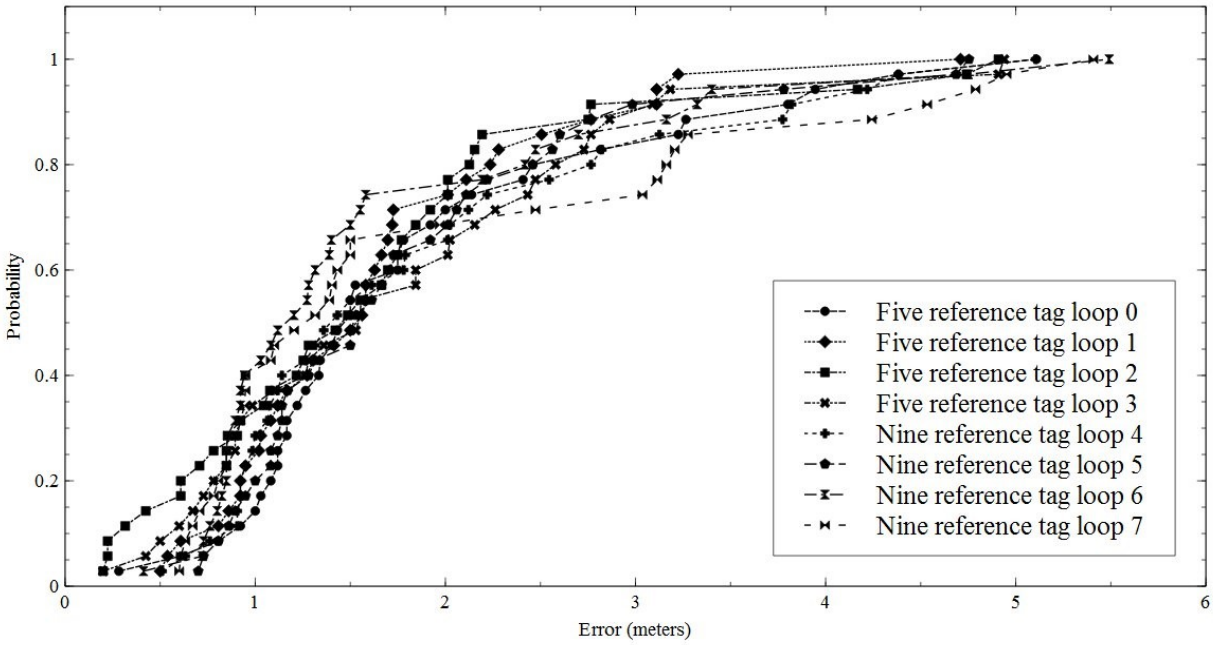


Fig. 51 CDF of error of same sampling size of nine and five reference tags estimation

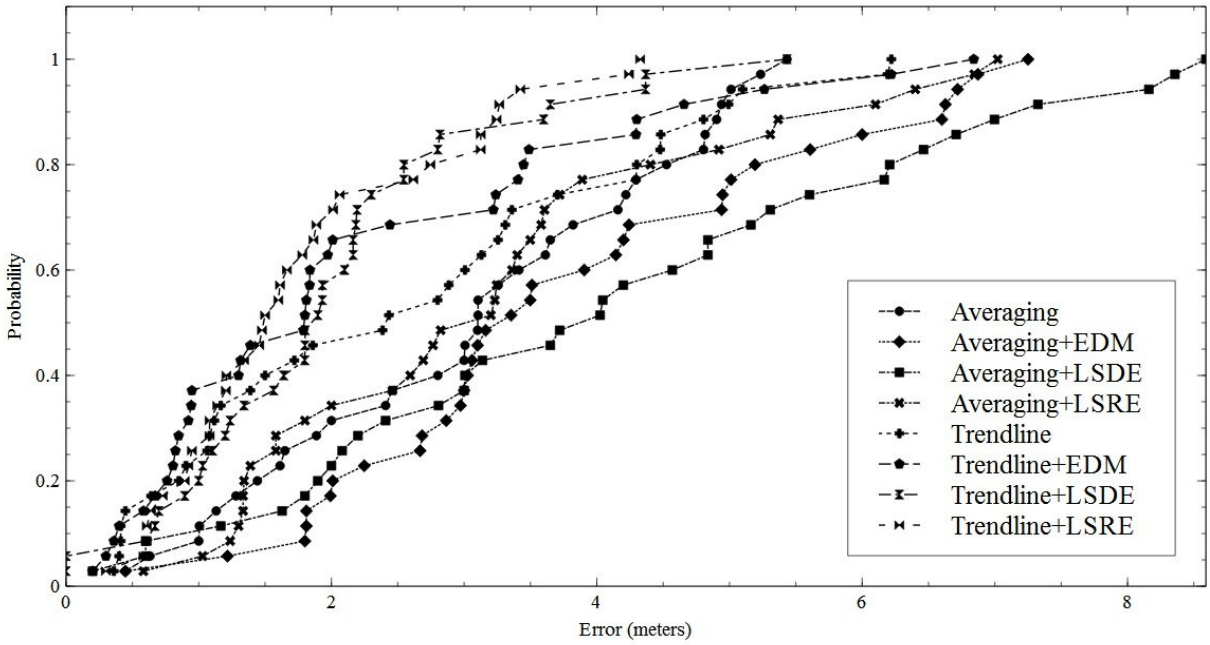


Fig. 52 CDF of error of nine reference tags with one loop

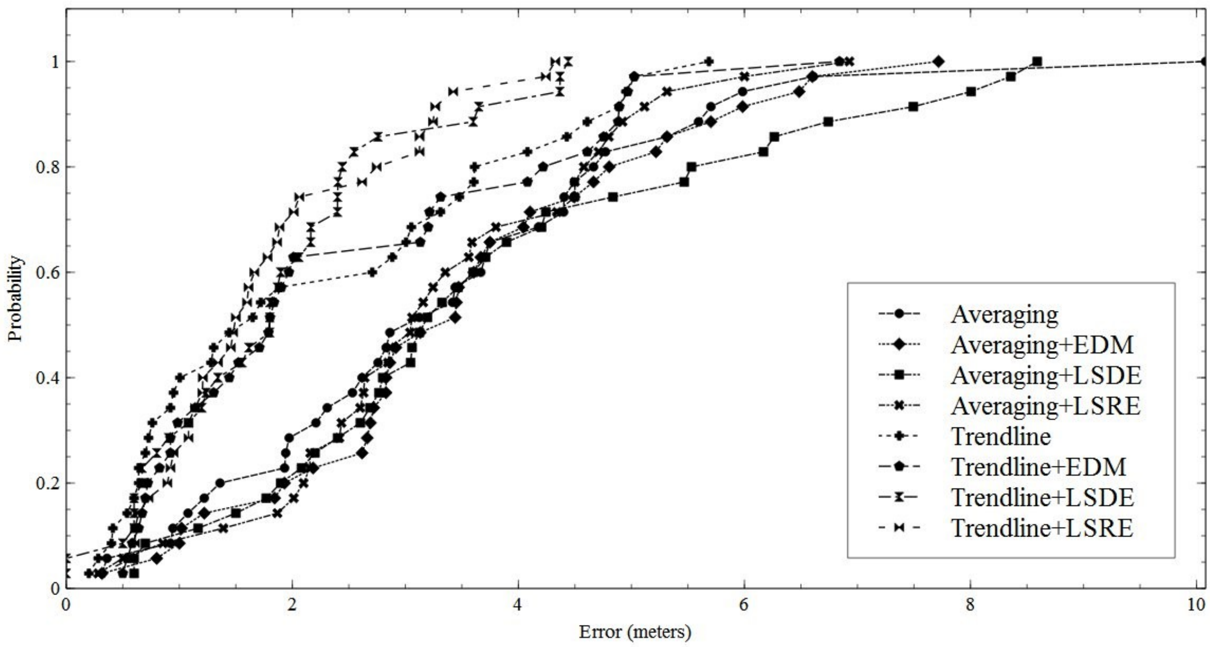


Fig. 53 CDF of error of nine reference tags with three loops

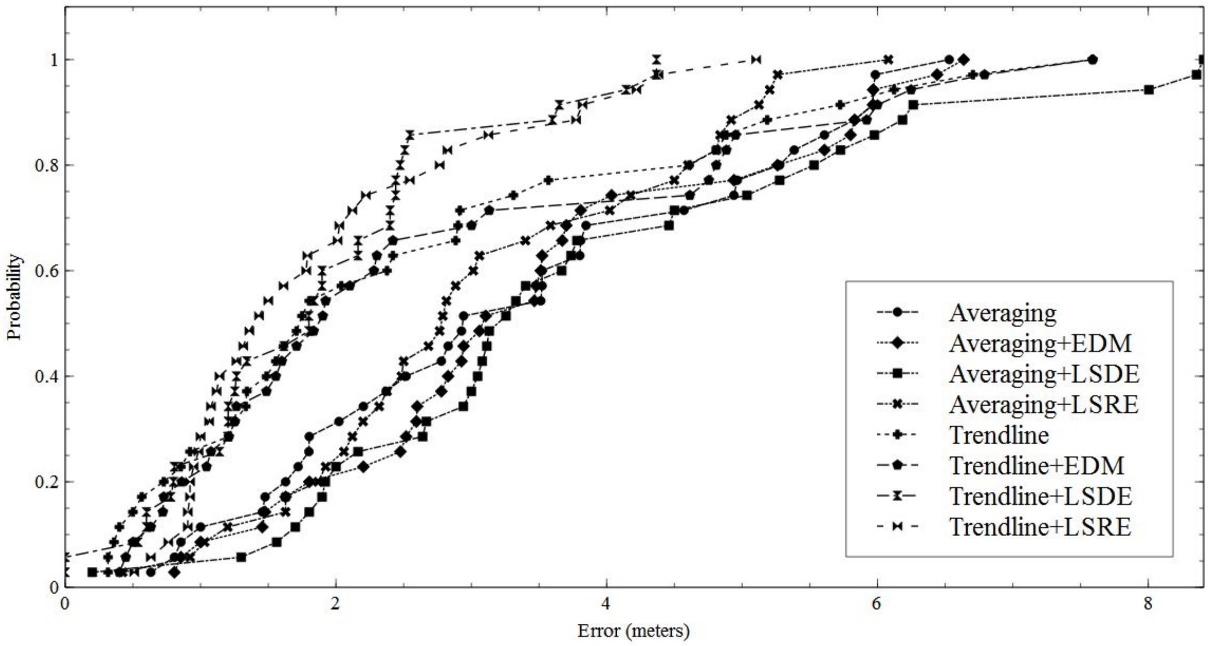


Fig. 54 CDF of error of nine reference tags with four loops

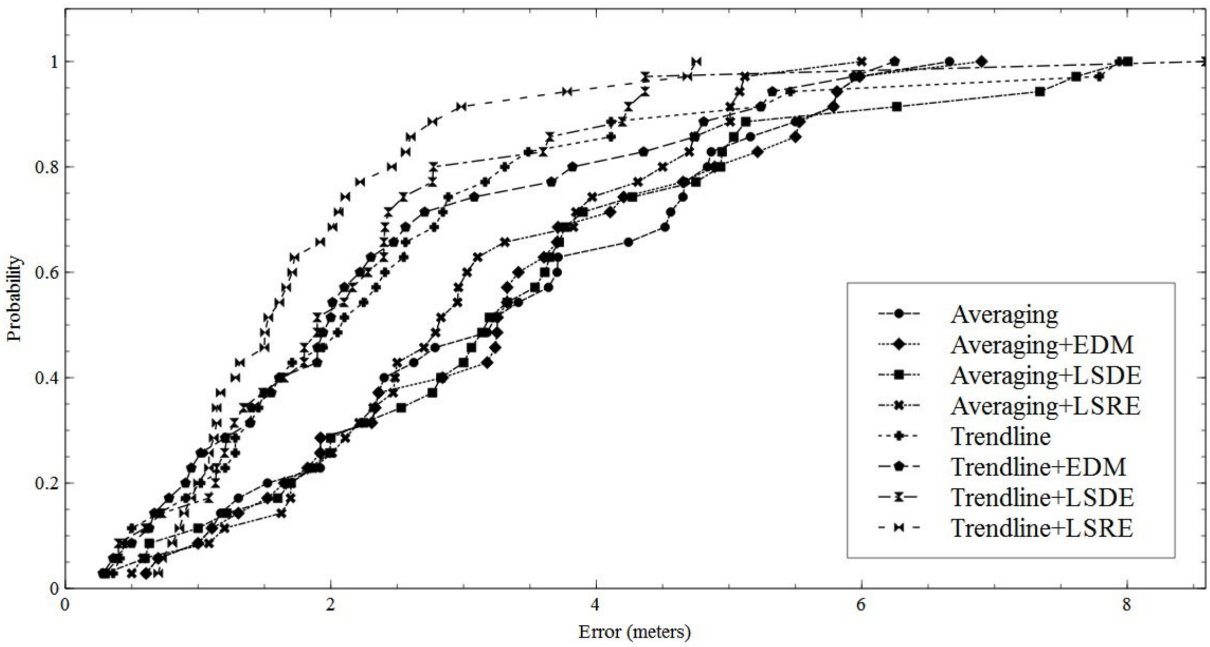


Fig. 55 CDF of error of nine reference tags with five loops

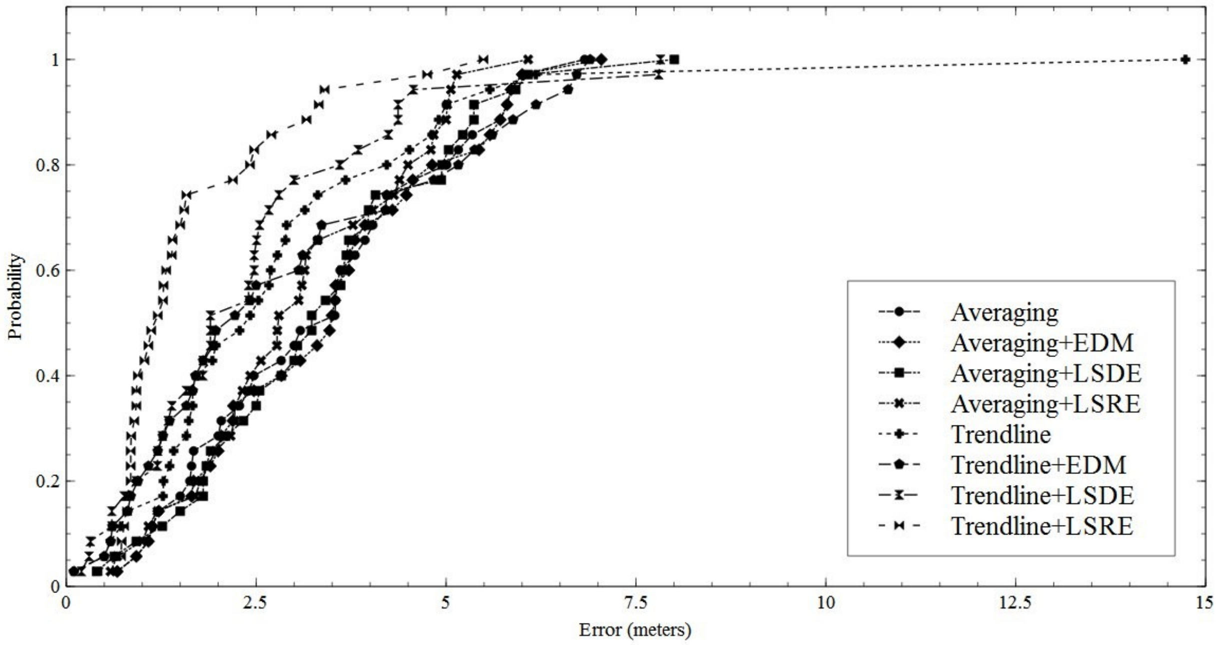


Fig. 56 CDF of error of nine reference tags with six loops

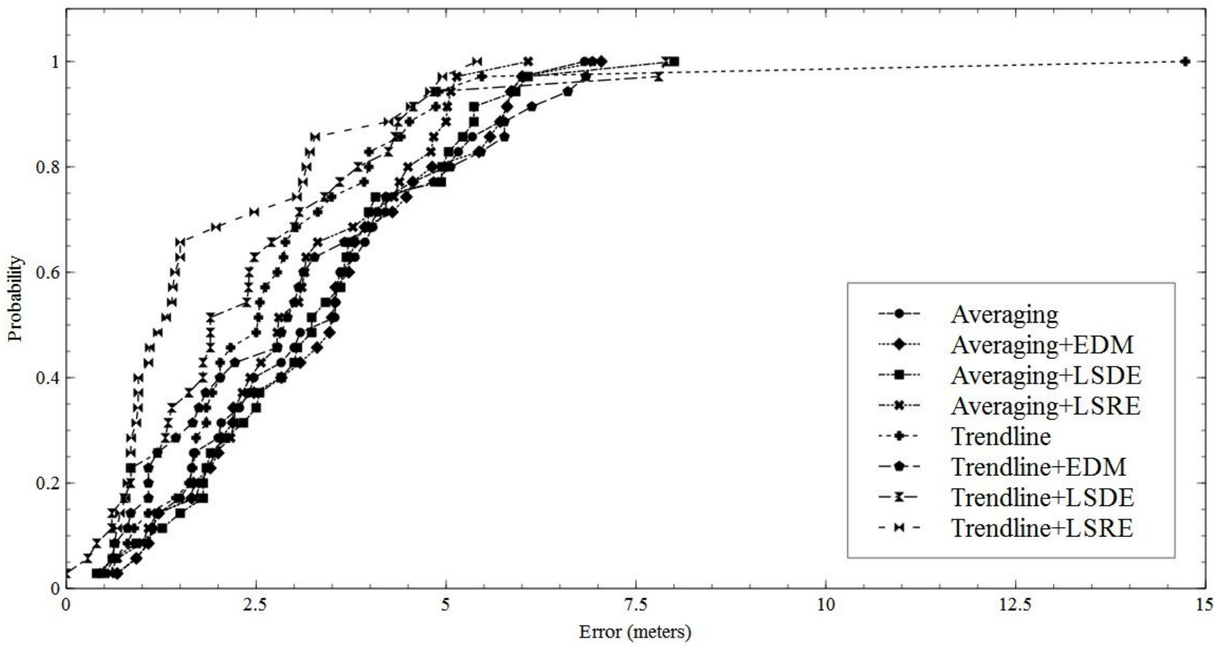


Fig. 57 CDF of error of nine reference tags with seven loops

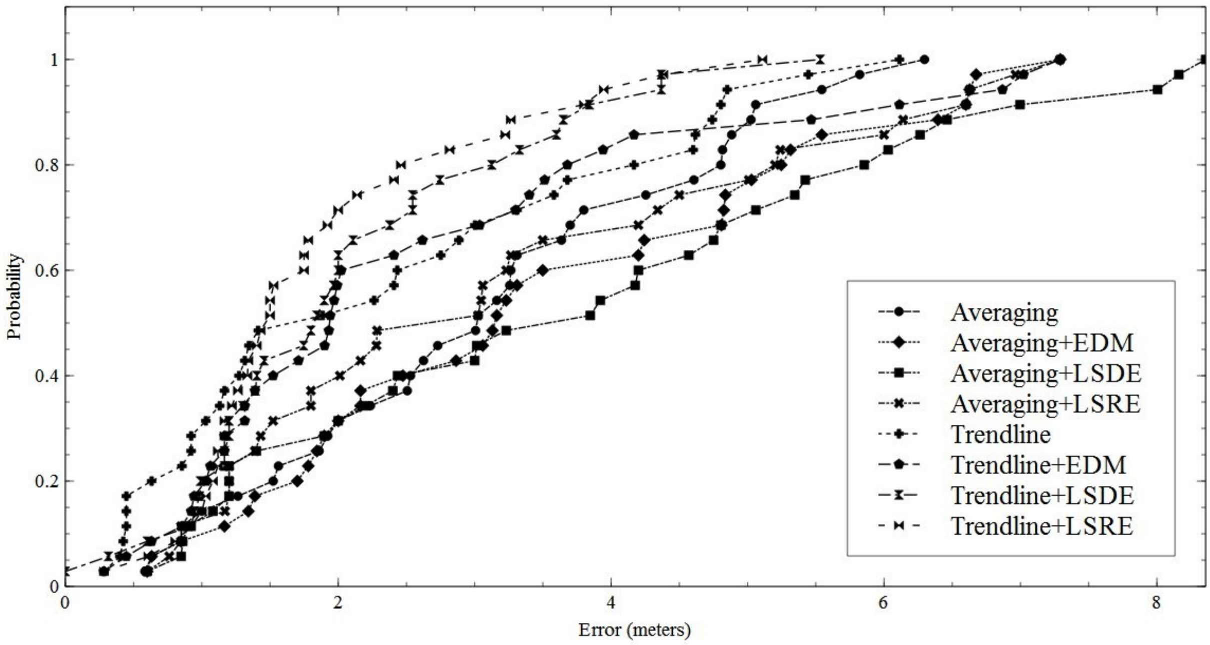


Fig. 58 CDF of error of five reference tags without loop

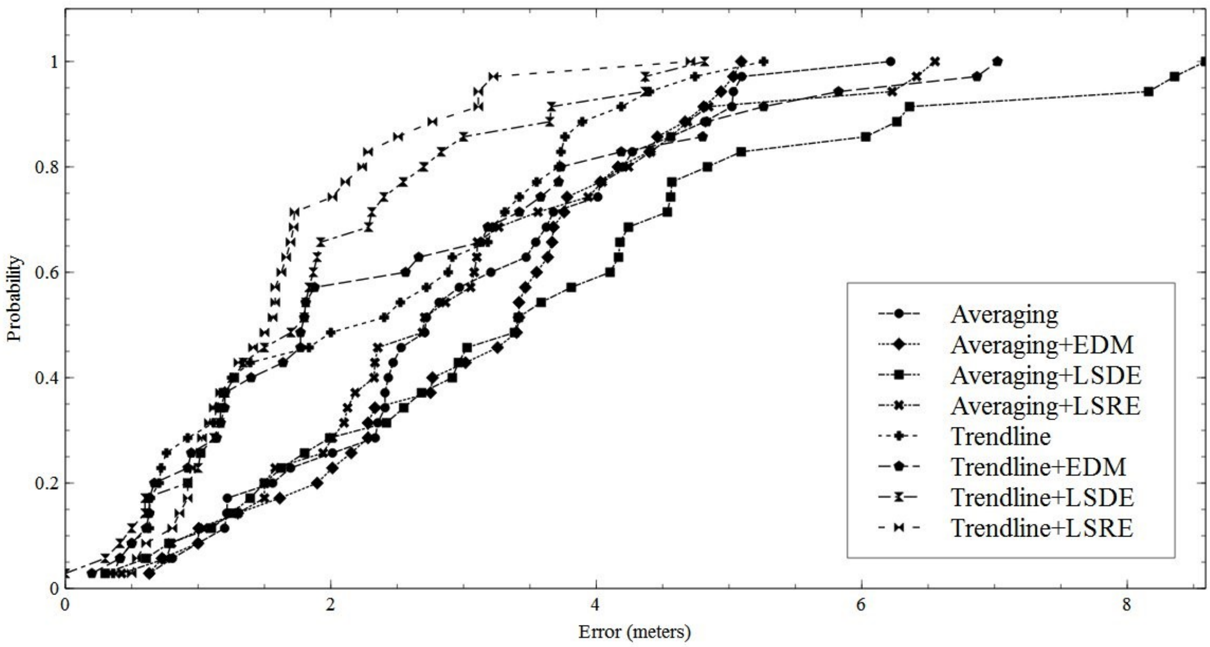


Fig. 59 CDF of error of five reference tags with one loop

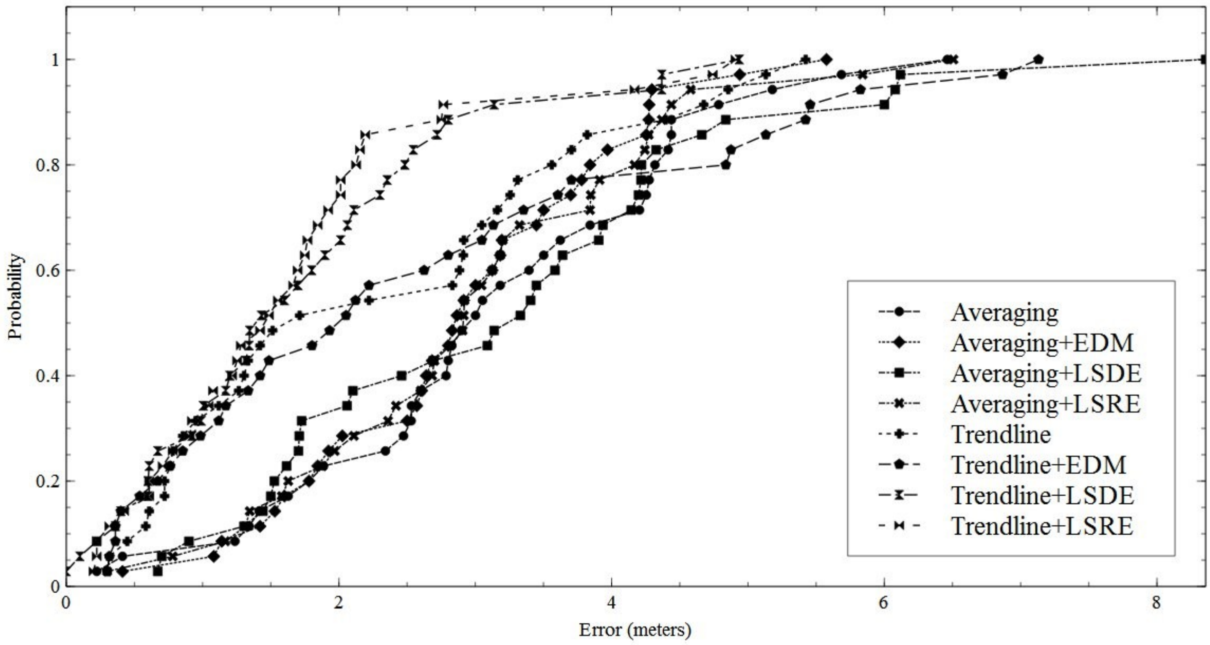


Fig. 60 CDF of error of five reference tags with two loops

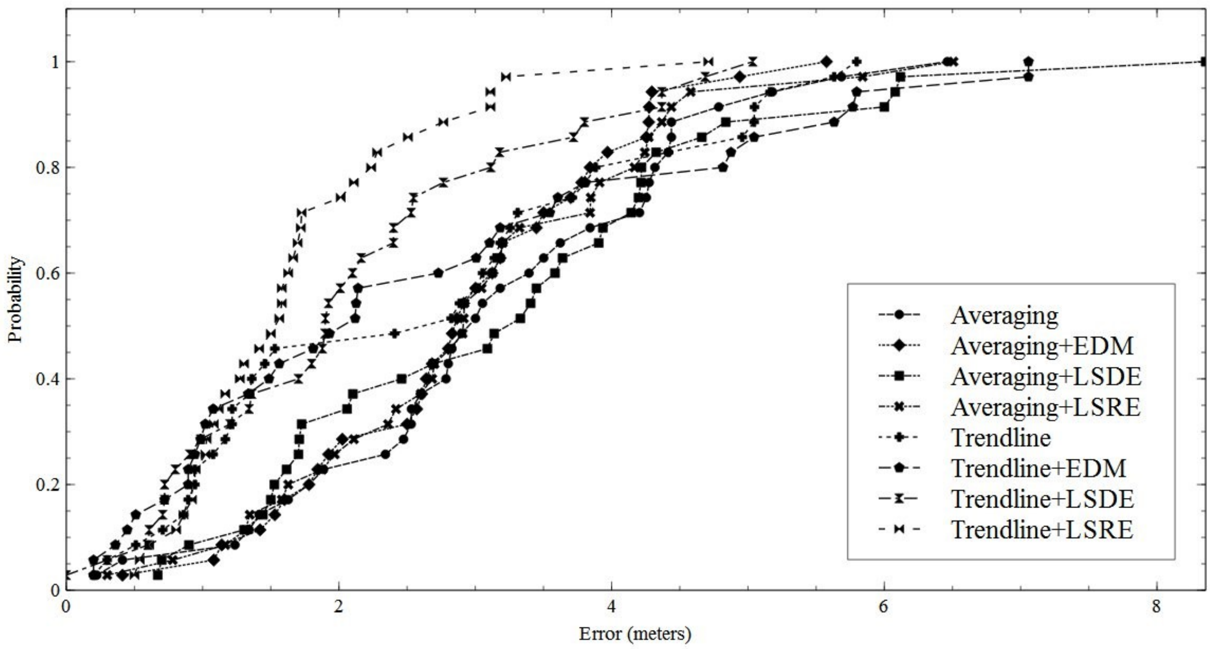


Fig. 61 CDF of error of five reference tags with three loops

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