UNIVERSITY OF SOUTHAMPTON
Faculty of Engineering, Science and Mathematics
School of Electronics and Computer Science

A thesis submitted for M.Phil Degree

The Localization for Wireless Sensor Networks

by Chenyang QU

Supervisor: Prof. Mark Zwolinski

December 19, 2007

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
SCHOOL OF ELECTRONICS AND COMPUTER SCIENCE

A thesis submitted for M.Phil Degree

by Chenyang QU

In this thesis, we firstly review and introduce the state of the art techniques and systems for the positioning in different application area, and classify them into five aspects for discussion and comparison. We mainly focus on researching the localization schemes of wireless sensor networks for outdoor environment, including the range-based and range-free schemes. In the range-free schemes, the simulation and analysis would be given by distance measurement and position estimation separately. By comparing their results and considering the hardware constraints, we make the suggestion of the optimal combination of range-free scheme in different requirement and environment for WSNs localization.

Contents

List of Figures

List of Tables

Nomenclature

AOA	Angle of Arrival
BN	Beacon Node
DF	Direction Finding
EMS	Electromagnetic Spectrum
FFC	Federal Communications Commission(US)
GPS	Global Positioning System
MDS	Multidimensional Scaling
$NLOS$	Non-line-of-sight
$RSSI$	Received Signal Strength Indicator
RX	Receiver
SN	Sensor Node
SNR	Signal to Noise Ratio
SVD	Singular Value Decomposition
$TDOA$	Time Difference of Arrival
TOA	Time of Arrival
TX	Transmitter
ULA	Uniform Linear Array
$WSNs$	Wireless Sensor Networks

Acknowledgements

I would like to express my deepest gratitude to my parents, who always give me self-giving supports. My heartfelt gratitude also goes to Professor Mark Zwolinski , my supervisor. Without his constant encouragement and guidance, this thesis could not have reached its present form. Finally, I would like to thank my friends Xianqiang Ren, Simon Ogg, Reuben Wilcock, Leran Wang, Arash Ahmadi etc., who gave me their helps and advices during the study and live in Southampton.

Chapter 1

Introduction

1.1 Motivation

In 1991, Mark Weiser described his vision of pervasive (or ubiquitous) computing, which aims at supporting human activities with computing, communication capability and a large number sensors that are deeply integrated into our daily lives. This was a vision too far ahead of its time, limited by the hardware technology [4][5]. Over a decade of technology progress, the increasing embedded and mobile devices coupled with ad-hoc, wireless networking have made the idea possible. One of the key technologies for pervasive computing is to implement networked microsensing with cheap, small, low power and smart sensors that are also capable of wireless communication. By collecting information from a large number of such wireless sensors we can get a multi-dimensional view of an event, such as combining the information on position, temperature, acoustic data, images etc, and the network can be applied to various areas. Especially it can be used for critical environments and locations e.g. continued unmanned surveillance, toxic locations and geographical detection.

With such a large scale, dynamically changing, and robust sensor network is usually associated the issue of its location. Apparently, it is necessary to identify each sensor nodes with their physical locations in the network. However, in a network of densely distributed sensor nodes, location discovery can be a significant design challenge. Because of the constraints in size, capabilities and cost of construction of sensor nodes, it is impractical to apply traditional GPS (Global Positioning System) receivers at each sensor node[6], besides the sensor network may be deployed in regions where satellite signals cannot be received. Hence a significant amount of work has been reported on both sophisticated algorithms and wireless hardware designs in recent years that enable wireless nodes in a large network to determine their locations without fully depending on GPS.

Since Integrated Circuit (IC) technology has been well developed in the past 20 years, wireless communication devices have become more and more powerful and flexible. Meanwhile many research teams started relative project, example: Project Aura at Carnegie Mellon University, Endeavour at UC Berkeley, Oxygen at the MIT and Portalano at the University of Washington [4] etc. People are working on different areas and have created many different positioning schemes. These schemes tends to two categories, they are range-based and range-free. The former one is based on absolute distance(range) measurement or angle estimation of point to point, such schemes include RSSI[7], TOA[8], TDOA[6], AOA[9], TPS[10], Spotlight[11] etc. Acknowledging that the additional hardware usually needed in range-based methods, researchers have worked on alternate range-free methods, which only use regular wireless modules. Such schemes are APS[12], APIT[13], Generic localized algorithm[14], Convex positioning[15], DAPS[16], Amorphous system, MDS-MAP[17], n-hop[18], GPS-free[19], SPA, AHLos[20], SeRLoc[21] etc. There are also some relative algorithms for location-aided routing, collaborative signal processing, and optimization of communication tasks, energy consumption in the network[22][23][24][7] and low cost, low complexity, small sensor nodes to be randomly deployed in a given target area and automatically determine their positions with respect to some reference points (or beacon nodes) [25][26][27][6][28].

The aim of this research is to focus on outdoor positioning for wireless sensor networks within a few metres accuracy using radio frequency signal. In this thesis, we make three major contributions. First, by considering limited capabilities of nodes in WSNs, we review and select some algorithms and different schemes for outdoor distance measurement and positioning. Second, we simulate and compare those algorithms in detail. It provides us to study the impact of error on each step and derive the optimal combination. Finally, we give our conclusion and results of WSNs positioning in different circumstance.

In next section, we briefly introduce the classification of existing position systems and discuss the key factors of WSNs. Later in Chapter 2, we present a review of the range-based localization techniques, such as time of flight, received signal attenuation and angle of arrival, comparing their advantages and disadvantages. In Chapter 3, the ad hoc network and range-free positioning techniques will be introduced. We also discuss three distance estimation algorithms and positioning algorithms. In Chapter 4, we simulate all selected range-based and range-free algorithms, mainly focusing on range-free algorithms. The performance will be shown in detail. Consequently, we propose the best combination algorithm for WSNs positioning. The conclusion and future work are in the last Chapter.

1.2 Self-positioning system and algorithm

Generally speaking, self-positioning system has been in two phases. In the first phase, researchers mainly concentrate on designing positioning systems with infrastructure or special equipments. They are including RADAR[25], Active Bat[1], Active Badge[29], Cricket system[8][2], MotionStar[30], RadioCamera[31], Active Office[27], Easy Living[8], SpotON[32], HiBall Tracker[33], Parc TAB[34], Smart Floor[35], Smart Rooms[36], 3D-iD[37], Where Net[38] etc. Recent a few years, people started to investigate in low-cost, small-size, positioning system without infrastructure for ad-hoc network, which is a local area network or other small network method often associated with wireless devices. The connection is established temporarily for the duration of one session. Wireless devices may search for target nodes that are out of range by flooding the network with broadcasts that are forwarded by each node.

But how can we sort out such huge number of, and increasing systems and algorithms? Here we give our comparison for some examples in five aspects.

1.2.1 Physical position and symbolic position

The positioning system used to provide two different type results, physical position and symbolic position. For example, $36^o7'17''N$, $111^o36'19''W$ is the physical position on the earth, which can be obtained by GPS receiver. However, symbolic position is still useful in some circumstance, especially in fire alarm system. For instance, the firemen want to know the fire in which room rather than its actual physical location. Such symbolic positioning system includes Active Badge[29] and Easy Living[8]. Certainly, in some situations, symbolic position can convert to physical position, vice versa.

1.2.1.1 Global Positioning System (GPS)

GPS is the widely used and vital technology for determining position and for navigation. There are 24 satellites in the GPS constellation plus 3 satellites for backups. GPS satellites are arranged in six orbital planes, providing timing and location service by sufficient satellites for any position on the surface of the earth. Since the time difference of arrival (TDOA) technique is used in GPS, the satellites are equipped with very accurate atomic clocks, which have accumulated error of 1 billionth of a second every three hours. It can be used as precise time reference as well.

Some inexpensive GPS receivers can locate positions about 15 metres for approximately 95 percent of measurements. More expensive differential units usually provide 1 to 3 meters resolution for 99 percent of the time [39]. Since a simple civilian GPS receiver costs around 50 pounds and can be used outdoors only, it is too expensive to apply for sensor nodes in the network, only suitable for determining the absolutely geographic location as references for a small number of land markers (or BNs).

1.2.1.2 Active Badge

The first and arguably archetypal indoor badge sensing system, the Active Badge location system, which was developed at Olivetti Research Laboratory, now AT&T Cambridge, consists of a cellular proximity system that uses diffuse infrared technology [29, 40]. The system provides indoor individual locations by determining their Active Badge. The device worn by personnel transmits a unique infra-red signal every 10 seconds. Each office is equipped with one or more networked beacon sensors which detect these transmissions and collects the data to a central server. The server provides an application programming interface for using the data. The current version of the badge incorporates a small microprocessor, offering bi-directional communication and a 48 bit address. The Cambridge group also designed one of the first large software architectures for handling this type of location data[41].

However, the limitations and difficulties of Active badge are fluorescent lighting or direct sunlight, as with any diffuse infrared system. Even indoors, strong interference will come near windows. Since diffuse infrared has an effective range of several metres, in a larger room the system would needs multiple beacon sensors.

1.2.2 Tightly coupled system and loosely coupled system

Tightly coupled system means all the reference points (or Beacon Nodes) are placed on fixed positions, and wired to central controller. The reference points in loosely coupled system are distributed randomly with wireless cooperation. Most of the tightly coupled systems (Active Bat, Active Badge, MotionStar and HiBall Tracker) can provide high accurate and real-time positioning for indoor environment, and are easy to be synchronised the time of reference points. But the extensity is restricted by the fixed distribution. Recent a few years, some systems such as Cricket, AHLos are adopted loosely coupled scheme with more flexible in allocation and less accuracy.

1.2.2.1 MotionStar Magnetic tracker

Electromagnetic sensing offers a classic position-tracking method [30]. The large body of research and products that support virtual reality and motion capture for computer animation often offer modern incarnations of this technology.

These tracking systems generate axial DC magnetic-field pulses from a transmitting antenna in a fixed location. The system computes the position and orientation of the receiving antennas by measuring the response in three orthogonal axes to the transmitted field pulse, combined with the constant effect of the earth's magnetic field. Tracking systems such as MotionStar sense precise physical positions relative to the magnetic transmitting antenna. These systems offer the advantage of very high precision and accuracy, on the order of less than 1mm spatial resolution, 1 ms time resolution. Disadvantages include steep implementation costs and the need to tether the tracked object to a control unit. The sensors must remain within 1 to 3 metres of the transmitter, and accuracy degrades with the presence of metallic objects in the environment [40].

1.2.2.2 Active Bat

After *Active badge*, AT&T researchers developed the *Active Bat* [1] location system, which uses an ultrasound time-of-flight technique to provide 3D location, orientation information and more accurate physical positioning than *Active Badges*. A short pulse of ultrasound is emitted from a transmitter (a Bat) carried by the user. At the same time the controller sends the radio frequency request packet, it

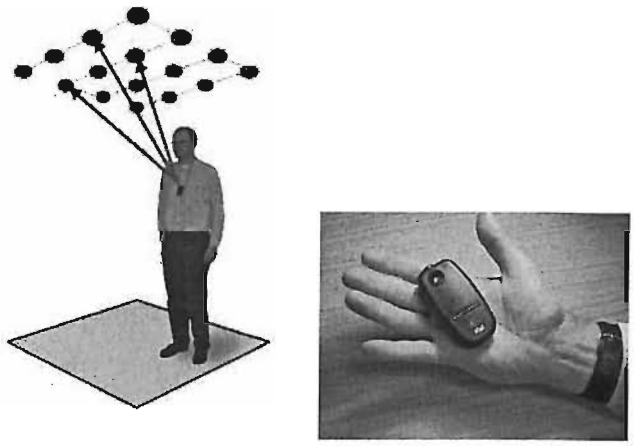

(a) (b)

FIGURE 1.1: Illustration of a user and beacon receivers 1.1(a) and The Active Bat tags[1] 1.1(b)

also sends a synchronized reset signal to a grid of ceiling-mounted receivers in a wired serial network. Each ceiling receiver measures the time interval from reset to ultrasonic pulse arrival and computes its distance from the Bat. Three or more such distances would be enough for determining the 3D position of the Bat 1.1(a).

The Bats measure $7.5cm \times 3.5cm \times 1.5cm$, as shown in Fig. 1.1(b), and are powered by 3.6V. Each Bat has a unique 48-bit code, and is linked with the fixed location system infrastructure using a bidirectional 433MHz radio link. The system can locate Bats positions accurate to around 3cm in three dimensions. Using ultrasound time of flight this way requires a large fixed-sensor infrastructure throughout the ceiling and is rather sensitive to the precise placement of these sensors. Thus, scalability, ease of deployment, and cost are disadvantages of this approach [40].

1.2.2.3 Cricket System

Cricket (Shown in Fig. 1.2.2.3), an indoor location system for pervasive and sensor-based computing environments and urban areas, provides applications of positioning running on handhelds, laptops and sensor nodes with precision of between 1 and 3 cm. The system uses a combination of RF and ultrasonic technologies. Wall and ceiling-mounted beacons transmit RF advertisement with a concurrent ultrasonic pulse. Listeners attached to devices and mobiles listen for RF signals, and upon receipt of the first few bits, listen for the corresponding ultrasonic pulse.

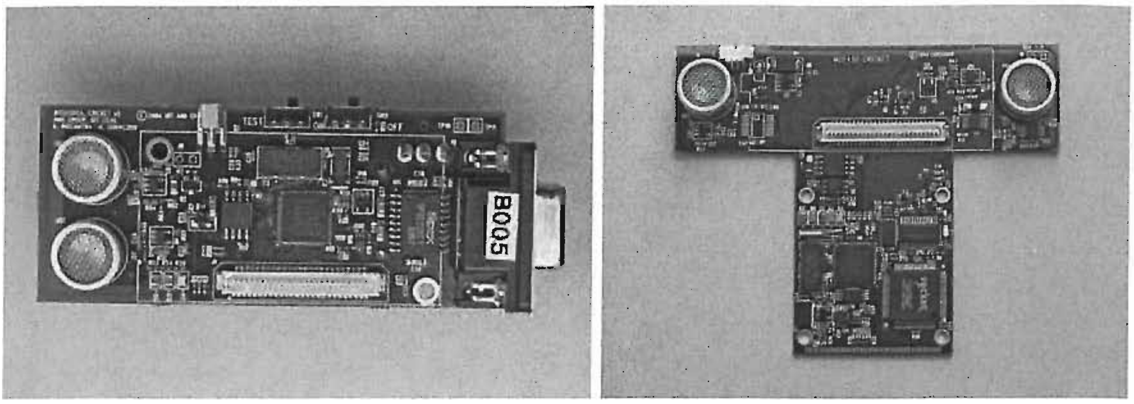


FIGURE 1.2: The listeners of Cricket system[2]

When the pulse arrives, the listener obtains a distance estimate for the corresponding beacon by taking advantage of the difference in propagation speeds between RF (speed of light) and ultrasound (speed of sound). The listener correlates RF and ultrasonic samples and estimates the distance. A randomized algorithm allows multiple uncoordinated beacons to coexist in the same space [1, 2].

A Cricket listener (as shown Fig.1.2.2.3) attaches to the host device using an RS232 serial connection. The Cricket beacon and listener are identical hardware devices under software control.

Like the Active Bat system, Cricket uses time-of-flight data and a radio frequency control signal, but this system does not require a grid of ceiling sensors with fixed locations because its mobile receivers perform the timing and computation function. Cricket implements both the time-of-flight and proximity techniques. Receiving multiple beacons lets receivers triangulate their position. Receiving only one beacon still provides useful proximity information [40]. Since the Cricket system uses active beacons and passive listeners, it scales well as the number of listeners increases. However, the fundamental limit of range-estimation accuracy used in Cricket would be no different than Active Bat.

The disadvantages include a heavy computational burden and consequently power consumption problem for dealing with ultrasonic and RF signals on the mobile devices.

1.2.3 Centralized computation and Distributed computation

In centralized computation network, all the positioning information was collected and calculated by a central unit (or a server), such algorithm including convex optimization and MDS-MAP[17]. The advantage is no limitation of computation and memories, hence we can get relative precise results. The drawback is that high communication and energy consumption are demanded on the nodes closed to central computing unit. Once those intermedial nodes ran out of power, the central unit would lose contact and be isolated from the far-end sensor nodes.

The distributed computation requires more capability of computing and the cooperation between nodes. It would be suitable for the static WSNs positioning with less positioning computing requests.

1.2.4 Range-based positioning and Range-free positioning

Range-based positioning uses nodes to nodes distances or angle to achieve trilateration, or multilataration for estimation the location. Range-free method usually only needs the connectivity of the networks for positioning. Some typical techniques of range-based positioning includes RSSI, TDOA, TOA and AOA. Although people tried to improve these algorithm for low-power and low-cost, the additional hardware can still hardly be avoided. TOA needs high precise time synchronization between the nodes. TDOA was limited by propagation range of ultrasonic (about 20 to 30 metres) and suffered with NLOS effect. AOA requires the special antenna that would be impractical to adopt on small and low-cost nodes. However, some range-based schemes are still worth to develop, which we will discuss them in next Chapter.

Acknowledging that the cost of hardware required by range-based positioning algorithms may be inappropriated in relation to the cost of the WSNs, researchers have changed to alternate range-free solutions. These range-free schemes use only regular radio transceivers as basics for localization; hence, they do not incur any additional hardware cost. The connectivity of the network plays an very important role in range-free algorithm, it gives the significant impact on the accuracy of the position results.

1.2.5 Fine-grained localization and coarse-grained localization

According to the content of positioning information, we can divide the system into two types. Using the strength of signal, time, or angles to locate the nodes, we call this type as fine-grained localization. For coarse-grained localization, it usually uses some technology (or proximity) to sense whether the unknown nodes closed to reference points, then to estimate the position, such system including Active badge, convex, ParcTAB and Smart floor.

1.2.5.1 RADAR System and PinPoint system

A Microsoft Research group has developed RADAR, a building-wide tracking system based on the IEEE 802.11 WaveLan wireless networking technology [25]. RADAR measures at the access points (or base station), the signal strength and signal-to-noise ratio of signals that wireless devices send for creating a Radio Map. A Radio Map is a database of locations in the building and the observed (or estimated) signal strength of the beacons emanating from the access points as recorded at these locations [42]. The advantage of the RADAR system is that it uses the same infrastructure that provides the building's wireless networking. But the object it is tracking must support a wireless LAN, which may be impractical on small or power-constrained devices. The RADAR system can determine objects to within about 3-4 metres of their actual position with 50 percent probability.

There is another indoor RF system using the 3D-ID RF tag system built by the PinPoint Corporation [43]. Antennas planted around a device emit RF signals at 2.4GHz. Tags, acting like RF mirrors, transmit a response signal at 5.8GHz along with an identification code. Various antennas receive the signal, and send the results to cell controllers, which triangulate the reflections to determine the tag's position. The accuracy of estimation depends on the number of antennas, and so far it achieves about 1-3 metres.

1.2.6 Active positioning and Passive positioning

In active mode, the sensor node (SN) will send a signal to the settled beacon nodes (BNs), when it requests for positioning. By collecting the information from BNs, the position of the SN would be estimated by a calculation unit. The active mode

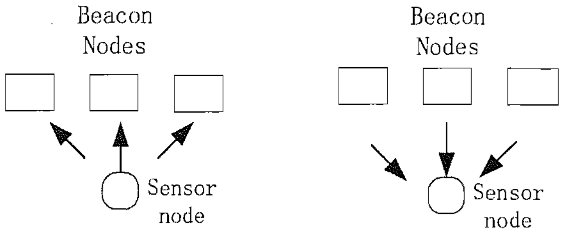


FIGURE 1.3: Active mode and Passive mode

has better perform at tracking, since the simultaneous distance estimation can be achieved at the multiple BNs. In passive mode, the beacon nodes periodically broadcast a message to all sensor nodes that signal can reach. Passive mode is superior to active mode in a high density and stable network [2].

1.3 The key factors of WSNs self-positioning system

To further investigate and analyse these algorithms, we introduce six important factors here.

Positioning accuracy (resolution)

Positioning accuracy, usually the ratio of error range and the transmission range of nodes, is the most important factor in all positioning systems. For 2-D grid system, the accuracy depends on the size of grid, such as RADAR and RadioCamera etc.

Anchor node (or Beacon node) density

The density of reference nodes is another important factor to evaluate the positioning system. The positions of reference points can be estimated by GPS or placed manually. If 10% nodes used GPS receiver as reference points, the cost of whole network would rapidly increaced 10 times [44].

Unknown node density

The higher unknown node density, means the more communication confliction in the network, and may cause the block of information transmission. The density of nodes always is represented by average connectivity in WSNs. The connectivity directly affect the performance of some range-free algorithms, such as DV-hop.

Fault tolerant

Because of multipath propagation, fading, distortion and NLOS, blind spot of RF signal, battery lifetime, physical damage,etc. existing in the real environment, the nodes in WSNs may have the adaptive capability to self-calibrate and reorganize to minimize the error.

Power consumption

Power consumption is the most important issue in WSNs, since it directly related to computation, communication period and frequency, memory size.

Cost

There are several cost in different aspects. For time, it contains the cost for construction time, calibration time and positioning time. For space, we need to think about the cost of the number of nodes, and device size etc.

Chapter 2

Range-based Positioning Techniques

So far the existing location positioning methods vary for different demands and environments. There are currently a large number of range-based schemes in the literature, each of which makes a different geometric approximation [45]. However, these range-based positioning methods adopt a few basic techniques, e.g. received signal strength indicator(RSSI), time of arrival(TOA). For implementation of these methods, a set of reference points (or beacon nodes(BNs)) would be needed, which have been placed and fixed in the known locations. In this chapter, we present and discuss five different range-based schemes for sensor nodes.

2.1 Received Signal Strength Indicator (RSSI)

The received signal strength indicator technique is employed to measure the power of the signal at the receiver and estimate the distance by knowing the transmitter power and the path loss model. For example, a signal from transmitter A to receiver B will be attenuated by a factor proportional to $1/r^2$ in a ideal free space, where r is the distance between A and B [46]. In WiFi network, transmission rate is determined by the signal strength .

Fig.2.1 illustrates that a sensor node estimates the distances(R_1, R_2 and R_3) from three (or more) beacon nodes (BNs) to compute its position in a 2-D plane by using lateration method. The major disadvantages of this method are that non-linear signal attenuation, multipath reflection, non line-of-sight conditions, and

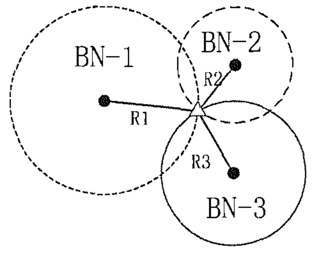


FIGURE 2.1: Determining position by using RSSI

many obstructions might lead to erroneous distance estimates. There are some techniques using a combination of RSSI and other adaptive algorithm that may improve the performance, as proposed in using multidimensional scaling (MDS) to reduce error accumulation [7]. However, the increased complexity of sensor nodes and nonuniform propagation environments make RSSI methods unreliable and inaccurate [6].

2.2 Time of Arrival(TOA) and Time Difference of Arrival(TDOA)

By recording the time of signal travel from transmitter to receiver, we can calculate the distance with the known constant prorogation speed. The position can be estimated in the same way as shown in Fig.2.1. Apparently, the major problem of TOA is the time synchronization in TXs and RXs. For high propagation speed RF signal, the well-synchronized clocks on TXs and RXs are required. For 1 metre distance, RF signal needs about 3.3ns to travel, which means 3.3ns mistake or delay would cause 1 metre range estimation error. So far it is impractical to sustain high precise time synchronization in nano-level on the low cost sensor nodes, neither they perform as transmitters nor a receivers. One of the solution is to adopt the relatively low propagation speed signal. In despite of the limited transmission range and the additional transducer, ultrasonic would be better choice than RF in this scheme. Comparing with RF signal, ultrasonic would need about 2.9ms to travel 1 metre in 21^oC.

If we can get the time synchronization on the fewer number beacon nodes, and each individual SN performs as a transmitter by sending request to the BNs, the time difference between each pair arrivals of the request at the BNs can be measured. According to hyperbola theorem, we can figure out a locus which the SN must lay on between two BNs. The intersection of two hyperbolic loci generated by three BNs will define the position of SN. That's the basic theory of TDOA.

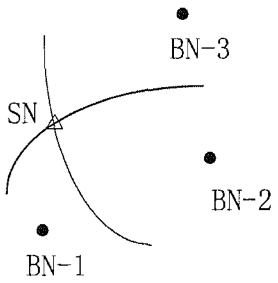


FIGURE 2.2: Example of determining position using two hyperbolic loci

In both TOA and TDOA methods, any factor affects the measurement of time could make the distance estimation inaccurate, such as multipath effect, hardware processing time at RX. By considering the cost and simplicity, TDOA would be a better way and more realistic in application. Hence, we discuss two TDOA methods in the following section.

2.2.1 Hyperbola Location Scheme

Here we introduce the hyperbola location scheme, in which the sensor node performs as a transmitter for positioning in active mode (as Fig.1.3). The hyperbola positioning method has been widely used, such as GPS, GSM positioning system and WCDMA system.

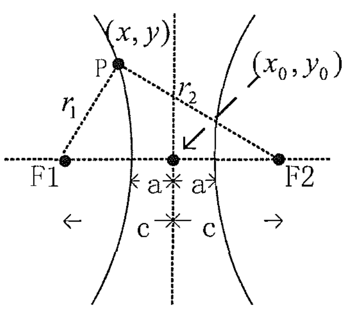


FIGURE 2.3: Hyperbola loci

According to the theory of hyperbola, a hyperbola is a conic section defined as the locus of all points P in the plane the difference of whose distances r_1 and r_2 from two fixed points (The foci F_1 and F_2) separated by a distance $2c$, is given by the positive constant k,

$$r_2 - r_1 = k \tag{2.1}$$

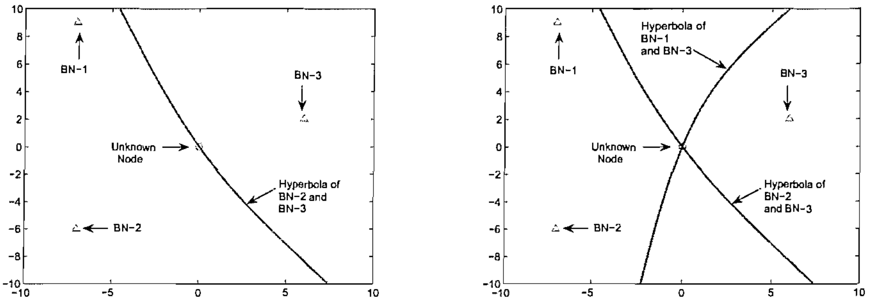
$$k = (c + a) - (c - a) = 2a \tag{2.2}$$

the formula of hyperbola is

$$\frac{(x - x_0)^2}{a^2} - \frac{(y - y_0)^2}{b^2} = 1 \tag{2.3}$$

where $b^2 = c^2 - a^2$.

Suppose F_1 and F_2 are two beacon nodes at known positions, then $2c$ and the centre point (x_0, y_0) are known numbers. The sensor node P sends a signal to F_1 and F_2, due to the different distances r_1 and r_2, the arrival time of the signal on F_1 and F_2 are different. We can derive k with the time difference of arrival and the same propagation speed. The hyperbola locus which transmitter P must lay on can be figured out. One locus can be obtained by two beacon nodes, three BNs then can at least give two loci. The intersection of two loci is the position of the transmitter.



(a) (b)

FIGURE 2.4: The simulation result of hyperbola positioning method

The Matlab simulation of hyperbola positioning with three beacon nodes is shown in Fig.2.4. For hardware implementation, the transmitter just needs to send a certain sequence for identification. However, we need the clocks on at least three beacon nodes to be well synchronized. The propagation time of RF signal for 1 metre distance is about 3.3ns, since

$$\frac{1}{3} \times 10^8 \approx 3.33 \times 10^{-9} = 3.33ns \tag{2.4}$$

Despite the difference of hardware processing (demodulation) time at each receiver, in order to achieve one metre positioning accuracy, the BNs have to have capability for detecting 3.3 ns time difference of arrival. The GPS receiver could achieve the requirement, or the beacon nodes are wired with the same oscillator and clock frequency.

2.2.2 Time Difference of Arrival Scheme

Here we present another TDOA method called TPS[10], in which each SN should have an individual clock or timer to record the time of the signal arrival and transmission. The major advantages are all the BNs and SNs do not have to be synchronized, and no transmission needed from SNs that could reduce the power consumption. The sketch of TPS method is shown in Fig.2.5.

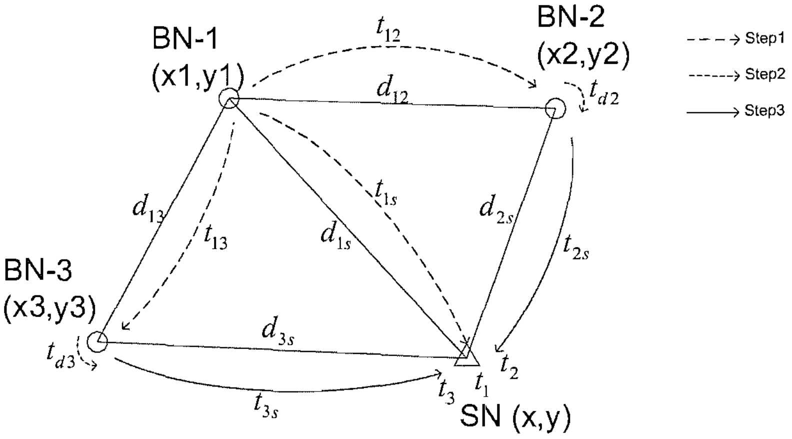


FIGURE 2.5: The sketch and procedure of TDOA scheme

As previously, BN-1, BN-2 and BN-3 are fixed reference points located on (x_1, y_1), (x_2, y_2) and (x_3, y_3), the corresponding distances d_{12}, d_{13} between them has to be estimated. In the first step, BN-1 broadcasts to all SNs and the other BNs periodically. The time of signal arrival on SN is denoted as t_1. Secondly, BN-2 and BN-3 will reply to BN-1 with the slightly different time, after they decoded the request from BN-1. The replied signal contains the information of processing time (modulation and demodulation time) at BN-2 and BN-3 (denoted as t_{d2} and

t_{d3}). Finally, the SNs receive the replied signals from BN-2 and BN-3 at the corresponding time of arrivals, which are t_2, t_3, t_{12}, t_{1s}, t_{2s} and t_{3s} are the time of signal propagation from node to node. Now we can get two equations by time

$$t_2 - t_1 = t_{12} + t_{d2} + t_{2s} - t_{1s} \tag{2.5}$$

$$t_3 - t_1 = t_{13} + t_{d3} + t_{3s} - t_{1s} \tag{2.6}$$

multiply with c (propagation speed) on both sides, we obtain

$$c(t_2 - t1) = d_{12} + c \cdot t_{d2} + d_{2s} - d_{1s} \tag{2.7}$$

$$c(t_3 - t1) = d_{13} + c \cdot t_{d3} + d_{3s} - d_{1s} \tag{2.8}$$

where $k_1 = c(t_2 - t_1) - d_{12} - c \cdot t_{d2}$ and $k_2 = c(t_2 - t_1) - d_{12} - c \cdot t_{d2}$. Since c, t_1, t_2, t_3, d_{12}, d_{13}, t_{d3} are known numbers, k_1 and k_2 can be found. Now we derive another three equations2.9-2.11 with three unknown numbers, x, y, d_{1s}.

$$(x - x_1)^2 + (y - y_1)^2 = d_{1s}^2 \tag{2.9}$$

$$(x - x_2)^2 + (y - y_2)^2 = (d_{1s} + k_1)^2 \tag{2.10}$$

$$(x - x_3)^2 + (y - y_3)^2 = (d_{1s} + k_2)^2 \tag{2.11}$$

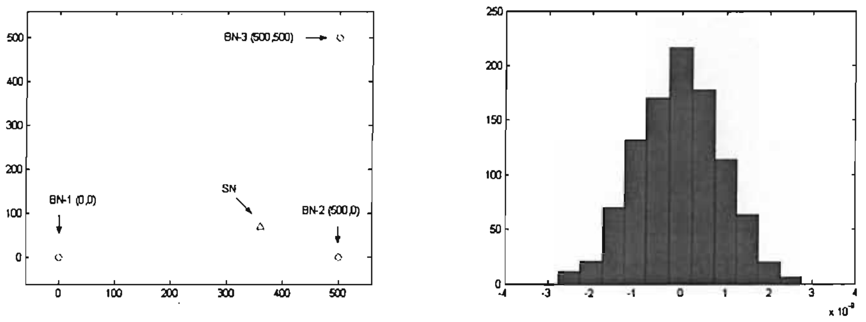
where x, y are the coordinates of SN, d_{1s} is the distance between BN-1 and SN.

For simplicity of simulation, we assume the three beacon nodes are located at (0,0),(x_2,0) and (x_3, y_3), the position of SN can be figured out by

$$x = \frac{-2k_1 d_{1s} - k_1^2 + x_2^2}{2x_2} \tag{2.12}$$

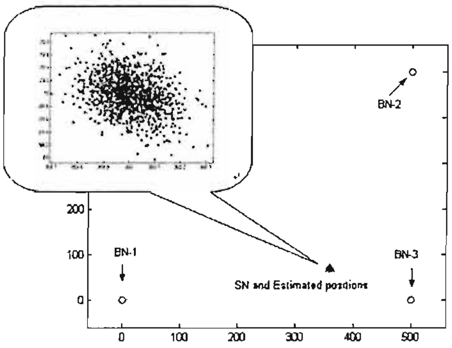
$$y = \frac{(2k_1x_3 - 2k_2x_2)d_{1s}}{2x_2y_3} + \frac{k_1^2x_3 - k_2^2x_2 + x_3^2x_3 + y_3^2x_2 - x_2^2x_3}{2x_2y_3} \tag{2.13}$$

In the simulation, we assume BN-1, BN-2 and BN-3 are located at (0,0), (500,0) and (500,500), as shown in Fig.2.6(a). The actual location of the sensor node is at (360,70), which is chosen by arbitrarily. We also introduce some error estimations of time difference at the BN-2, BN-3 and SN. The error are generated by Gaussian random process, the probability density function of the error is shown in Fig.2.6(b) with the range about -3ns to 3ns.



(a) Simulation of TDOA Scheme

(b) PDF of Gaussian random number



(c)

FIGURE 2.6: Simulation results of TDOA scheme

The estimated positions are shown in Fig.2.6. By enlarging the figure, we can see all the "stars"(estimated positions) are spreaded in 1 metre range around the centre point (actual position) SN(360,70).

2.3 Angle of Arrival(AOA)

If two beacon nodes (BNs) can estimate the received angles of the signal from sensor node (SN), and the distance between these BNs **M** is known. the position of SN can be figured out by only two beacon nodes as shown in Fig.2.7.

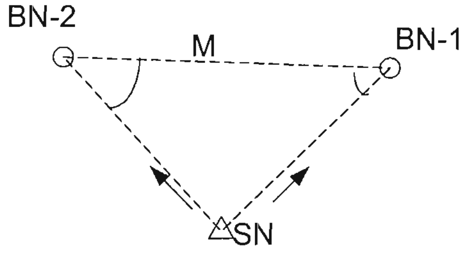


FIGURE 2.7: The sketch of AOA principle

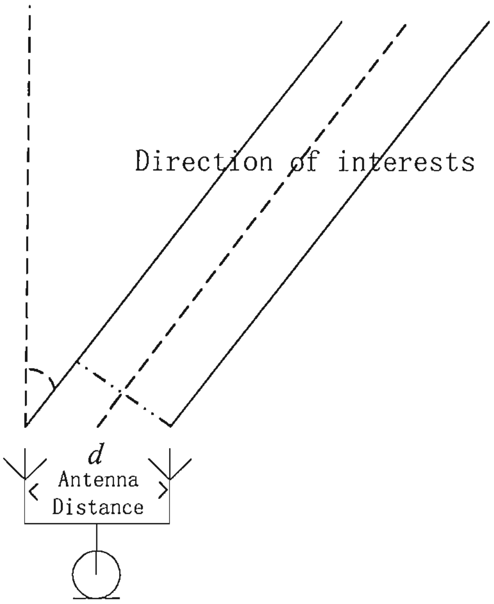


FIGURE 2.8: The antenna array for DF

Estimation of AOA, commonly referred to as direction finding (DF), can be accomplished either with a mechanically steered narrow beamwidth antenna or with an electronically steered array of antennas [47]. The latter would be more reliable and achievable for DF. Generally the antenna array is a uniform linear array (ULA) which antennas have equal interval spacing in a straight line. Due to a spatial frequency exists, when sampling a signal spatially, the sampling interval should be considered to avoid spatial aliasing subject to the spatial sampling theorem, which is shown below.

Oversampling:

$$d < \frac{c\pi}{\omega_{max}} \tag{2.14}$$

Critical sampling:

$$d = \frac{c\pi}{\omega_{max}} \tag{2.15}$$

Undersampling:

$$d > \frac{c\pi}{\omega_{max}} \tag{2.16}$$

where c is the propagation speed, is the angular frequency of signal, d is the sampling interval (Fig.2.8) which is the distance between two adjacent antennas. For 433MHz frequency signal, d is required about $34.6cm$. For 2.4GHz frequency signal, d is required to be $6.25cm$. Typically there are about $4 - 10$ antennas in such array for **DF**. Besides the algorithm selected, the accuracy of **DF** techniques depends on a number of factors, which include SNR, integration time, number of antennas, hardware non-idealities, and array calibration error [47].

The advantages of DF techniques are that a position location (PL) estimate may be determined with as few as two base stations, and no time synchronization between base stations is required. The disadvantages of DF system are that, firstly they require relatively large and complex hardware, because each antenna needs an individual filter and mixer for demodulation and increases the cost. Secondly the position estimate degrades as the mobile moves farther from the base stations, it becomes inaccurate for tracking.

2.3.1 Directional Antenna Scheme

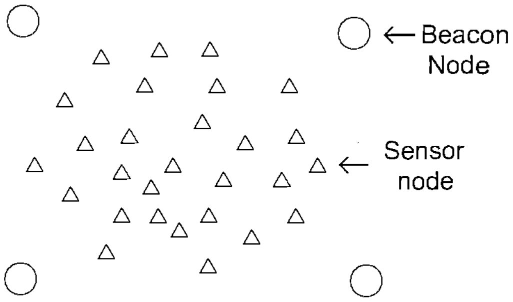


FIGURE 2.9: The sketch of network model

Now we introduce another directional antenna scheme. First we assume the sensor network model as depicted in Fig.2.9. The triangles represent sensor nodes (SNs) in the network with a large number, the circles represent the beacon nodes (BNs) which locate on known position as the reference points. The SNs in random positions collect data (such as temperature, humidity etc.) periodically, equipped simple processor, wireless transceiver, memory for limited data processing and communication. The information collected by SNs could be transmitted to BN or high level processor by using some routing algorithms, since the transmit power on SN may not be enough to reach BNs directly. However, in this positioning scheme all the SNs perform as receivers and do not need to directly transmit any data to BNs.

In Fig.2.9, four beacon nodes are shown. For 2-D positioning, we need at least three BNs as in Fig.2.10. These BNs have capabilities for sending wireless beacon signals throughout the sensor network.

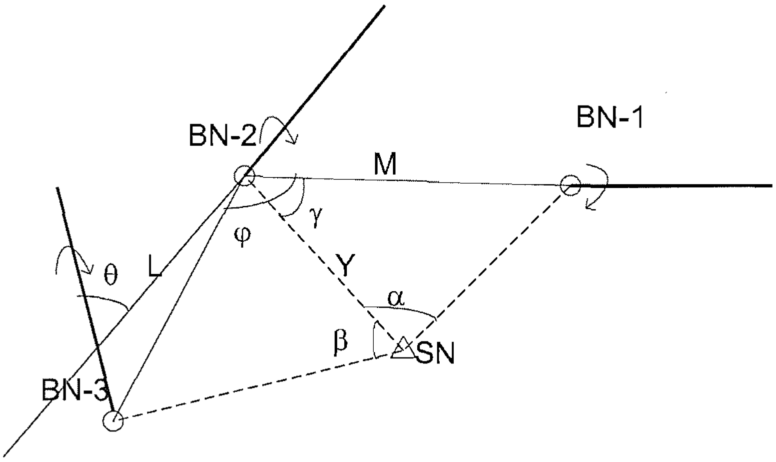


FIGURE 2.10: The model of rotating directional beacon signals for 3 beacon nodes

The aim is to let all the SNs distinguish between the signals transmitted by different beacon nodes and obtain their angular bearings with respect to the beacon nodes, so we assume that each beacon signal consists of a continuous RF carrier signal with different frequencies or different signature sequences (same carrier frequency) on a narrow directional beam that rotates with a constant angular speed ω degrees/s (shown in Fig.2.10). There is a constant angular separation of θ degrees between the directional beams for the three beacon nodes BN-1, BN-2 and BN-3, and θ can be any value.

The rotating directional beams may be implemented by directional antennas that are mechanically rotated as done in radar system, or it could be generated by an electronically steerable smart antenna[6]. The SN would not receive BN signal, if it's not on the interest direction of the BN antenna. Since the SN needs sufficient time to receive the whole transmitted information, the rotation speed depends on the data rate of BN. Consequently, each sensor node will receive periodic bursts from the three beacons.

The localization principle is based on a sensor node recording the times when it receives different beacon signals, and evaluating its angular bearings and location with respect to the beacon nodes by triangulation. Here we denote the times at which an SN receives the beacons signals from BN-1, BN-2 and BN-3 at t_1, t_2 and t_3, respectively. The time difference of arrivals can be translated to angular values as follows:

$$\alpha = \omega\tau_1 + \theta \tag{2.17}$$

$$\beta = \omega\tau_2 + \theta \tag{2.18}$$

where $\tau_1 = t_1 - t_2$ and $\tau_2 = t_2 - t_3$ are the differences between each two beams hitting on SN. θ is the angle difference between the beams, and it is known constant. Since the BNs are on the known positions, L, M and φ are already shown. Once we derive the α and β, the problem becomes a geometrical question, which can be solved by Eqn.2.17, and Eqn.2.18

$$\gamma = arctan[\frac{M \cdot sin\beta sin\alpha - L \cdot sin\alpha sin(\beta - \varphi)}{L \cdot sin\alpha cos(\beta + \varphi) + M \cdot sin\beta cos\alpha}] \tag{2.19}$$

$$Y = M\frac{sin(\alpha + \gamma)}{sin\alpha} \tag{2.20}$$

No matter what kind of wireless communication scheme, the same problems would be multipath and non-direct of sight (as shown in Fig.2.11(a) and Fig.2.11(b)). Reflections from surrounding objects or obstacles may cause the same BN signal to arrive at different times on SN, and make angular and positioning estimation error. To minimize this error, firstly, we need to keep the beamwidth of BN signal as narrow as possible, and set a threshold on SN to record the moment of the strongest burst for calculation. Secondly, the rotation speed of directional antenna should be relatively low (because of low data rate), in order to make sure the SN has sufficient time to recognize the BN signal. Thirdly, we can introduce more beacon nodes for observation. As in Fig.2.11(b), any three BNs can estimate the position of SN, and we can choose the most close result as the real position.

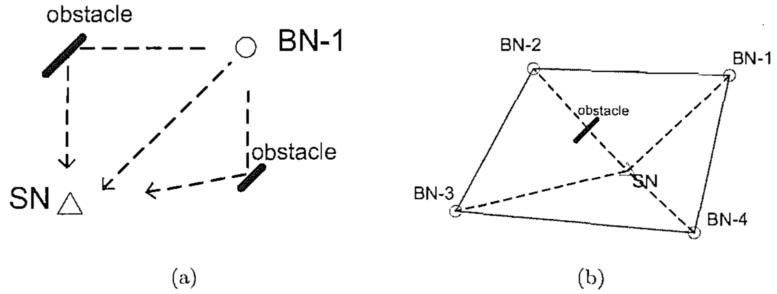


FIGURE 2.11: Multipath problem2.11(a) and Non-direct of sight situation2.11(b)

Previously, we assume all the positions of BNs are already known on the first step. Now we introduce 4, 5 or more BNs with GPS receivers, the complexity and cost would highly raise. Here is the method to solve the problem. Actually if we use more than 3 BNs in the network, only 2 BNs at known locations are enough to detect the rest of BNs. For instance, there are 4 BNs in the network (Fig.2.12), only BN-1 and BN-2 are on the known positions.

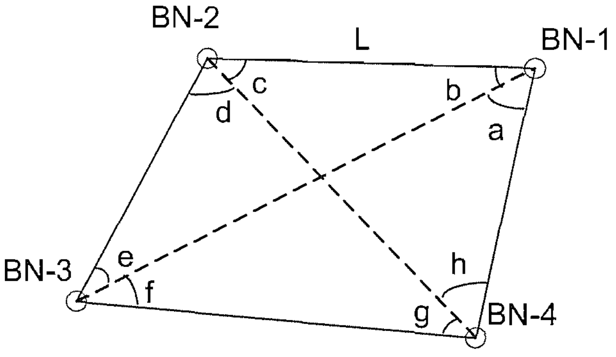
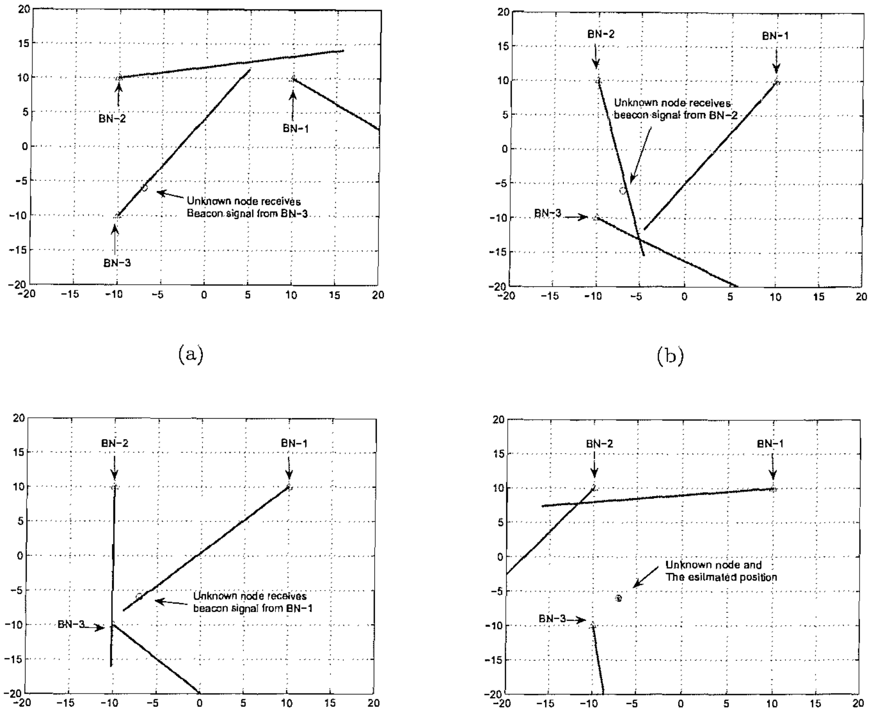


FIGURE 2.12: The method for BNs positioning

Now we just get the distance between BN-1 and BN-2 and L. By using the same way as SN positioning, any single BN can estimate the angles towards the other three BNs. Apparently, angles denoted as a to h can be easily found out. We get all angles and a constant distance L, any triangle in above figure would be solved. Hence, the positions of BN-3 and BN-4 have been located.

The simulation result of 3 beacon nodes using MATLAB has shown in Fig.2.13(a)-2.13(d). Sensor node only needs to record the time(t_1, t_2 and t_3) when it receives signal from BNs, then its position can be determined by the equation2.17-2.20.



(a) (b)

(c) (d)

FIGURE 2.13: The simulation of Directional antenna scheme

In this method, SN performs as a receiver in passive mode. It could be a very simple RF receiver, such as FM receiver. The sensor nodes do not need additional hardware complexity, and time synchronization. And the performance of the method is not affected by the density or number of sensor nodes in the network. The main source of error is the beamwidth of directional beacon signal. In existing products of directional antenna, the beamwidth can be within 15 degrees.

The difficulty of hardware implementation is also the part of directional antenna. For electronically steering, we have to refer antenna array, which mainly used on receivers. The size and cost of antenna array is relative high. For mechanical steering antenna, the constant rotation speed is a unmanageable problem.

2.4 Link Budgets

A huge network consists of dense sensor nodes, the constraints in size and construction cost for each node are critical. The limitation of transmit range of sensor node should be considered, not just for conserving battery power, but also for frequency allocation regulations. In many countries the transmission power must be lower than limitation (shown in Table 2.1) in unlicensed bands.

Frequency (MHz)	FFC REGS (US)	ETSI (Europe)	MPT (Japan)
902-928	$< 1000mW$	N/A	N/A
2400-2483.4	$< 1000mW$	$< 100mW$	N/A
2471-2497	N/A	N/A	$< 10mW$
5725-5875	$< 1000mW$	$< 100mW$	N/A

TABLE 2.1: International unlicensed Frequency allocations RF power limits

Here is the equation (Eqn 2.21) of link budget:

$$RxP = TxP + TxG - TxL - FSPL - ML + RxG - RXL \tag{2.21}$$

where the abbreviations are shown in Table 2.2

RxP	Received Power (dBm)
TxP	Transmitter output Power (dBm)
TxG	Transmitter antenna gain (dBi)
TxL	Transmitter Losses (dB)
FSL	Free space Loss (dB)
ML	Miscellaneous Losses (dB)
RxG	Receiver antenna gain (dBi)
RxL	Receiver Losses (dB)

TABLE 2.2: Specification of Link Budget Eqn.2.21

By considering the EMS regulations (Table.2.3) and the power limitation, we choose 433MHz as an example for calculating the link budgets. Some assumption must be made before calculation about transmit and receiver antenna gain values. For a simple dipole antenna, an assumption of 0 dB gain is reasonable. This number will be taken for the gain of both transmit antenna gain and receiver gain. The calculation procedures and results are shown in Table:2.4. Fig. 2.14

Frequency (MHz)	Transmit Power	Comments	Area
13.56	High	Very narrow bandwidth, ISM band, industrial plasma welding	World
303.825	Low	Car door alarm	Japan, Korea, USA
303.825	Medium	Car door alarm	USA, Australia
315.0	Medium	Car alarms, garage doors	USA, Canada, Italy
433.92	Medium	Car alarms, garage doors, telemetry	Europe
868.0-870.0	High	ISM band, data networks, telemetry	Europe
916.5	High	ISM Band, High power, telemetry, data networks	USA
2400	High	ISM band, Microwave, data networks, telemetry	World (Asia and Europe restrict bandwidth)

TABLE 2.3: Unlicensed international EMS regulations [3]

plots more results with 3 free-band frequencies. It implies that to obtain the same level of SNR, the high bandwidth signal requires the higher transmit power.

Effective Isotropic Radiated Power (EIRP)	10 dBm W≈ 10 mW
Free Space Path Loss (FSPL) $FSPL = 20log\frac{4\pi d}{\lambda}$	65.2 dB (for 100 metres range with 433MHz)
Ideal Noise Floor(with Temperature 200K) $N = KTB$ $= 1.38 \times 10^{-23} \times 200 \times 433 \times 10^{6}$	-119.2 dBm
Typical Noise Floor	-119.2 + 15 = -104.2 dBm
Resultant Downlink carrier to noise ratio (C/N_o)	$10 - 65.2 + 119.2 = 49dBm$

TABLE 2.4: Link Budgets

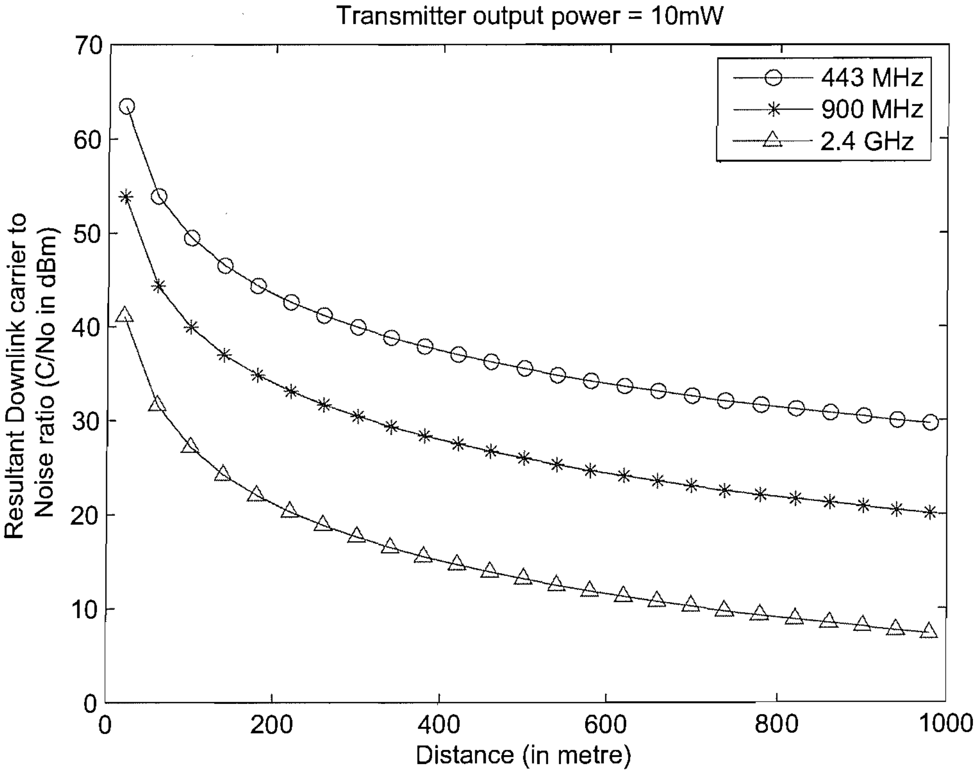


FIGURE 2.14: The Resultant Downlink C/No with 10mW TX power

Chapter 3

Range-free Positioning Techniques

At the beginning of this chapter, we firstly explain the term "ad hoc network". In computer network, ad-hoc is a local area network or other small network method which is most often associated with wireless devices. The connection is established temporarily for the duration of one session and requires without any infrastructure or base station. Wireless devices may search for target nodes that are out of range by flooding the network with broadcasts that are forwarded by each node. Connections are possible over multiple nodes (multihop ad-hoc network). The main features of ad hoc networks include large number of unattended nodes with varying capabilities, lack or impracticality of deploying supporting infrastructure [39]. What is necessary for these types of networks is a class of algorithms which are scalable, tunable, distributed, easy to deploy, and most importantly easy to maintain. Here we briefly introduce some range-free algorithms.

3.1 APIT

APIT[13] developed by researchers in University of Virginia , requires a heterogeneous network of sensing devices where a small percentage of these devices (percentages vary depending on network and node density) are equipped with high-powered transmitters and location information obtained via GPS or some other mechanism. The researchers refer to these location-equipped devices as anchors. Using beacons from these anchors, APIT employs a novel area-based approach to perform location estimation by isolating the environment into triangular regions between beaconing nodes Fig.3.1. A node's presence inside or outside of these triangular regions allows a node to narrow down the area in which it can potentially reside. By utilizing combinations of anchor positions, the diameter of the estimated area in which a node resides can be reduced to provide a good location estimate.

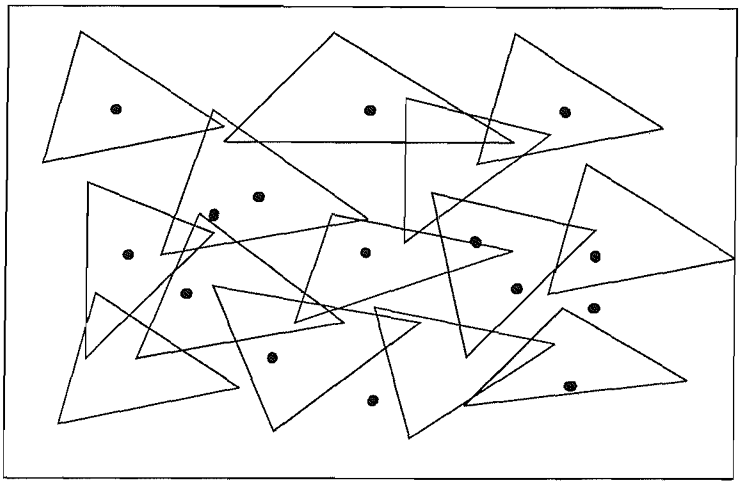


FIGURE 3.1: The example of area-based APIT algorithm

The theoretical method used to narrow down the possible area in which a target node resides is called the Point-In-Triangulation Test(PIT). In this test, a node chooses three anchors from all audible anchors (anchors from which a beacon was received) and tests whether it is inside the triangle formed by connecting these three anchors. APIT repeats this PIT test with different audible anchor combinations until all combinations are exhausted or the required accuracy is achieved. At this point, APIT calculates the centre of gravity (COG) of the intersection of all the triangles in which a node resides to determine its estimated position. The APIT algorithm can be broken down into four steps: 1) beacon exchange, 2)PIT testing, 3) APIT aggregation, and 4) COG calculation. These steps are performed at individual nodes in a purely distributed fashion.

3.2 Generic Localized system

S. Megnerdichiam, and S. Slijepcevic in UCLA have developed a generic localization algorithm for solving optimization problem in WSNs ad-hoc network [14], including five components: 1) data acquisition mechanism, 2) optimization mechanism, 3) search expansion rules, 4) bounding conditions, and 5) termination rules.

The data acquisition mechanism facilitates which sensed data is obtained from which node. The optimization mechanism provides a partial or complete solution to the targeted task. Search expansion rules indicate which nodes are best to contact next. Bounding conditions indicate which nodes should not be considered further, since information that they have is irrelevant for the final solution. Finally, termination criteria indicate when search expansion and optimization mechanism can be halted.

The idea is to request and process data only locally and only from nodes who are likely to contribute to both final solution as well as to provide good bounds to determine non-promising search directions. It is important to note that initialization may start from a single point (as in the case of minimal exposure path coverage) or multiple points (as in the case of location discovery). In the second case, the search is continued simultaneously on more than one cluster of communicating nodes. Note that the clusters can overlap.

The approach enables two types of optimization. In the first, one guarantees the percentage of nodes that are contacted, while trying to optimize the quality of solution. In the second, one provides guarantees on the quality of solution, while minimizing the number of nodes that are contacted and/or amount of communication.

There are two initiation steps which start the search at single or multiple locations. After that we enter a loop. The termination criteria are user specified and count either the number of contacted nodes or measures amount of communication in one case or how far we are from the final solution in the other case. The first step in the loop is to form or elaborate on partial solutions with the available information. The solution is next analyzed in terms of its distance from optimal and which direction (sensor nodes) should be contacted next. After that we terminate the search along all lines that will not yield the final optimal solution, governed by the bounding conditions.

3.3 AHLos and n-hop multilateration

Andreas Savvides proposed an algorithm (AHLos and n-hop multilateration primitive) based on a platform of wireless sensor node (called "Medusa")designed by UCLA, which equips ultrasonic transmitter for 3 metre range [20].

In this algorithm, the single hop multilateration operation performed by GPS is extended to operate on multiple hops. This enables nodes that are not directly connected to beacon nodes to collaborate with other intermediate nodes with unknown locations situated between themselves and the beacons to jointly estimate their locations. One of the main challenges in this problem is to prevent error accumlation inside the network. To prevent error accumulation, the node localization problem is set up as a least squares estimation problem with respect to the global network topology.

Collaborative multilateration takes place in three main phases: 1) formation of collaborative subtrees, 2) computation of initial estimates, 3) position refinement. During the first phase, the nodes form a well-constrained or over-constrained configuration of unknowns and beacons, the collaborative subtrees. This configuration forms a system of at least n non-linear equations and n unknown variables to be determined. Collaborative subtrees also ensure that each unknown member of the computation subtree has a unique possible solution. this prevents the iterative least squares refinement process in the first phase from computing estimates that are numerically correct but are not the correct solutions. The nodes that do not meet the criteria for collaborative subtrees cannot participate in this configuration. the position estimates for such nodes are determined later in a post -processing phase. In the second phase, each unknown node computes an initial estimate of its location based on the known beacon locations and the inter-node distance measurements.These initial estimates are used to initialize the refinement process in the third phase. The third phase computes a least squares estimate of the node locations. Finally, a post-processing phase uses the computed node estimates to refine the position estimates of nodes that could not participate in the computation subtree configuration. This phase has the similar functionality as the phase for computing initial estimates but it is more constrained but the newly computed location estimates in the computation subtree.

The first and second phases are independent from each other and can take place in parallel in an actual network. Phase three can start as soon as the first two phases are completed and it can terminate at different stages depending on the demands of the application. If computation is done at a central point (either a central computer for the whole network, or a local cluster head), the process will terminate when the unknown nodes receiver their position estimates. If the distributed computation form is used, then the processes termination depends on the demands of the application. If the application requires just an indication of proximity, the localization process can only perform the second phase and terminate. If more accurate localization is required, the distributed computation will continue until required precision is achieved.

3.4 Spotlight

The main idea of the Spotlight localization system [11] is to generate controlled events in the field where the sensor nodes were deployed. An event could be, for example, the presence of light in an area. Using the time when an event is perceived by a sensor node and the spatio-temporal properties of the generated events, spatial information regarding the sensor node can be inferred.

After deployment, the sensor nodes self-organize into a network and execute a time-synchronization protocol. An aerial vehicle (e.g. helicopter), equipped with a device, called Spotlight, flies over the network and generates light events. the sensor nodes detect the event and report back to the Spotlight device, through a base station, the timestamps when the events were detected. The Spotlight device computes the location of the sensor nodes.

There are several assumptions should be made for Spotlight system:

1. The sensor network to be localized is connected and a middleware, able to forward data from the sensor nodes to the Spotlight device, is present.

2. The aerial vehicle has a very good knowledge about its position and orientation(6 parameters: 3 translation and 3 rigid-body rotation) and it possesses the map of the field where the network was deployed.

3. a powerful Spotlight device is available and it is able to generate spatially large events that can be detected by the sensor nodes, even in the presence of background noise (dayligth).

4. a line of sight between the Spotlight device and sensor node exists.

Through performance evaluations of a real system deployed outdoors by researchers in University of Virginia, they obtained a 20cm localization error. A sensor network, with any number of nodes, deployed in a $2500m^2$ area, can be localized in under 10 minutes, using a device that costs less than $1000.

3.5 Range-free positioning algorithms

As we mentioned in Chapter 1, there are a number of localization systems have been proposed specifically for ad hoc networks. By considering the limitation of WSNs devices, researchers have sought alternate distributed, loosely coupled and range-free solutions to the localization problem in sensor networks. These solutions should be used by regular radio modules as basics for localization and do not incur any additional hardware cost[13]. Thus, the requirements of these algorithms should be:

1. self-organizing, do not depend on global infrastructure.
2. robust, be tolerant to node failures and range errors.
3. energy-efficient, require little computation and, especially, communication.

These requirements immediately rule out some of the proposed localization algorithms for sensor networks. We choose and simulate several range-free localization algorithms (N-hop multilateration[18], Ad-hoc positioning[12] and Robust positioning[48]). We carried out a thorough sensitivity analysis on three algorithms that do meet the above requirements to determine how well they perform under various conditions. In particular, we studied the impact of the following parameters: range errors, connectivity (density), and anchor fraction. Algorithms differ in position accuracy, network coverage. Given the different design objectives for the three algorithms, it is no surprise that each algorithm outperforms the others under a specific set of conditions. Under each condition, however, even the best algorithm leaves much room for improving accuracy and/or increasing coverage.

Fig.3.2 shows the example network topology. Note that anchor nodes have the same capabilities(processing, communication, energy consumption, etc.) as all other unknown position nodes. These nodes have the capability to measure the distance between directly connected neighbour nodes in the network. For example, by observing the RF signal strength the nodes can roughly estimate the distances. Poor range measurements can be compensated for by using many anchors or a high connectivity.

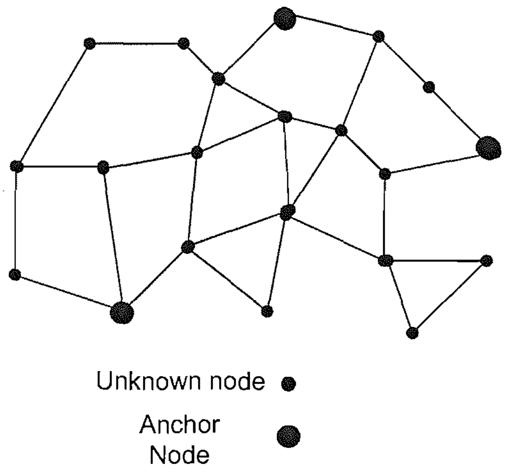


FIGURE 3.2: The example of network topology

3.5.1 Distance Estimation

3.5.1.1 Sum-hops

The simplest solution for determining the distance to the anchors is simply adding the ranges encountered at each hop during the network flood. The distance between two nodes, can be estimated by RSSI or just simply use the TX range of nodes. This is the approach taken by the N-hop multilateration[18] approach. The measurement starts at the anchors, who flood a message including their identity sequences, positions, and set path length to 0. Each receiving node adds the measured range to the path length and forward the message to neighbour nodes if the *floodlimit* allow it to do so. Another constraints is that when the node has received information about the particular anchor before, it is only allowed to forward the message if the current path length is less than the previous one.

Here is an example (shown in Fig.3.3), by adding the hop distances, we derive: distance from node A to node n is $5 + 6 + 5 = 11$; distance from node B to node n is 5; distance from node C to node n is $6 + 3 + 3 + 4 = 16$;

3.5.1.2 DV-hop

A disadvantage of Sum-hops is that range errors accumulate when propagating distance information over multiple hops. This cumulative error becomes significant for large networks with a few anchors (long paths) and poor ranging hardware. A robust alternative is to use topological information only by counting the number of

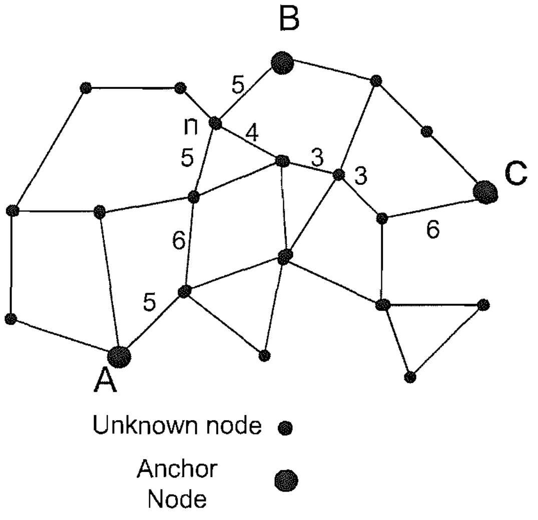


FIGURE 3.3: The example of sum-distance measurement

hops instead of summing the ranges. This method is called DV-hop by Niculescu and Nath[12].

DV-hop essentially consists of two flood waves. After the first wave, which is similar to Sum-distance, nodes have obtained the position and minimum hop count to at least *floodlimit* anchors. The second calibration wave is needed to convert hop counts into distances. This conversion consists of multiplying the hop count with an average hop distance. Since anchor nodes A, B and C are on known positions, the distances between them can be derived, divides that by the number of hops to find the average hop distance. Then anchor A send the average hop distance as calibration message to the network. The distances from unknown node to anchors can be derived by multiplying the numbers of hops with average hop distance.

Fig. 3.4 shows that the distance AB is 20, BC is 15, and the least numbers of hops are 4 and 3. So $(20+15)/7 = 5$ is the average hop distance. Now we can get the distance from A to n is $5 \times 3 = 15$; distance from B to n is 5; distance from C to n is $5 \times 4 = 20$.

For further improving the accuracy, there's another method called Differential APS [16]. The underlying idea of this algorithm is motivated by Differential GPS. The algorithm uses at least four anchor nodes in 2D positioning. The unknown node uses error correction factors obtained from the nearest anchor node to estimate the effective distance to the other three anchor nodes, subsequently, to reduce the cumulative distance error over the multiple hops. The error correction factors

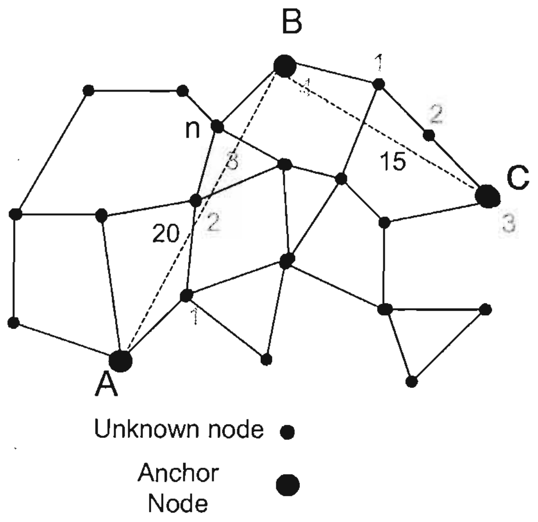


FIGURE 3.4: The example of DV-hop method

are calculated by the similar method as DV-hop, but each anchor has its own correction factors to the other anchors.

3.5.1.3 Smooth algorithm

Since the hop count in DV-hop method is always an integer value, researches found an enhance method to get a more precise hop value. By averaging of all the neighbour's hop counts to an anchor node, we can obtain a relative accurate hop count which formula is shown as Eqn.3.1

$$S_i = \frac{\sum_{j \in nbrs(i)} h_j + h_i}{|nbrs(i)| + 1} - 0.5 \tag{3.1}$$

with i as the centre node, $nbrs(i)$ as the neighbour's node of i, and h_i and h_j as the hop count to a certain anchor.

3.5.1.4 Euclidean

Niculescu and Nath have proposed another method in Ad-hoc positioning [12], named Euclidean, that is based on the local geometry of the nodes around an anchor. Again anchors initiate a flood, but forwarding the distance is more complicated than in the previous cases. When a unknown node has received messages from two neighbours that know their distances to the anchor, and to each other, then the unknown node can calculate the distance to the anchor by geometric method.

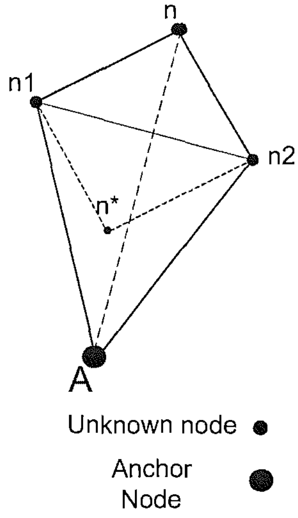


FIGURE 3.5: The example of Euclidean method

Fig.3.5 shows that node A has two neighbours $n1$ and $n2$. If the distances of all lines (non-dashed) in Fig.3.5 can be estimated, we would get two possible distances, one is from A to n and the other is from A to $n*$. To determine which one is the real distance that we are looking for, we may use another node to make the judgement.

3.5.2 Position Estimation

Now we can obtain the distances from an unknown node to all anchor nodes by one of four above methods. For locating the position of the unknown node, ad-hoc positioning[12] and Robust positioning[48] use lateration. N-hop multilateration[18], uses a simpler method, people used to called it, Min-Max. And we are also interested in MDS-Map[17] method. But firstly, we introduce the most common method, called lateration.

3.5.2.1 Lateration

Lateration is a very simple method for deriving position, and it also called triangulation. From the estimated distances d_i, anchor positions (x_i, y_i) and unknown position (x, y), we got the equations:

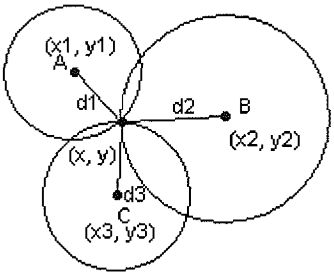


FIGURE 3.6: The sketch of Lateration

$$
\begin{aligned}
&(x_1 - x)^2 + (y_1 - y)^2 = d_1^2 \\
&\vdots \\
&(x_n - x)^2 + (y_n - y)^2 = d_n^2
\end{aligned}
$$

The equation can be linearised by subtracting the last equation from the first $n-1$ equations.

$$
\begin{aligned}
&x_1^2 - x_2^2 - 2(x_1 - x_2)x + y_1^2 - y_2^2 - 2(y_1 - y_2)y = d_1^2 - d_2^2 \\
&\vdots \\
&x_{n-1}^2 - x_n^2 - 2(x_{n-1} - x_n)x + y_{n-1}^2 - y_n^2 - 2(y_{n-1} - y_n)y = d_{n-1}^2 - d_n^2
\end{aligned}
$$

Reordering the terms gives a proper system of linear equations in the form $Ax = b$,

$$
A = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ \vdots & \vdots \\ 2(x_{n-1} - x_n) & 2(y_{n-1} - y_n) \end{bmatrix} \tag{3.2}
$$

$$
b = \begin{bmatrix} x_1^2 - x_2^2 + y_1^2 - y_2^2 + d_2^2 - d_1^2 \\ \vdots \\ x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 + d_n^2 - d_{n-1}^2 \end{bmatrix} \tag{3.3}
$$

The system is solved using a standard least squares approach: $\hat{x} = (A^T A)^{-1} A^T b$.

3.5.2.2 Min-Max

Lateration is quite expensive in the number of floating point operations that is required. For 3D positioning, we need to use at least 4 anchors, the calculation would increase hugely by finding the intersection point of 4 spheres.

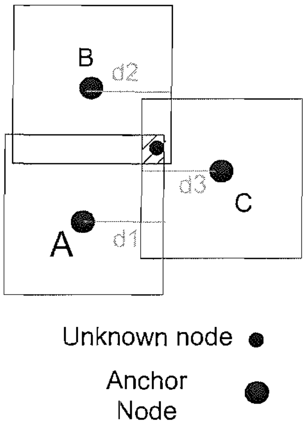


FIGURE 3.7: The sketch of Min-Max method

A much simpler method is presented by Savvides et al. as part of the N-hop multilateration approach. The main idea is to construct a bounding box for each anchor using its position and distance estimated, and then determine the intersection of these boxes. The position is set to the centre of the intersection box. Fig.3.7 illustrates the Min-Max method for a node with distance estimates to three anchors. The boundary box of anchor A is created by adding and subtracting the estimated distance d_1 from the anchor position (x_1, y_1):

$$[x_1 - d_1, y_1 - d_1] \times [x_1 + d_1, y_1 + d_1]$$

The intersection of the bounding boxes is computed by takeing the maximum of all coordinate minimums and the minimum of all maximums:

$$[max(x_i - d_i), max(y_i - d_i)] \times [min(x_i + d_i), min(y_i + d_i)]$$

The final position is set to the average of both cornet coordinates.

3.5.2.3 MDS

MDS has its origins in psychometrics and psychophysics. It can be seen as a set of data analysis techniques that display the structure of distance-like data as a geometrical picture [49]. MDS starts with on or more distance matrices (or similarity matrices) that are presumed to have been derived from points in a multidimensional space. It's usually used to find a placement of the points in a low-dimensional space (two or three dimension). There are many types of MDS techniques, including classical MDS, replicated MDS, weighted MDS. In this research, we only focus on classical metric MDS.

Classical metric MDS is the simplest case of MDS: the data is quantitative and the proximities of objects are treated as distances in a Euclidean space [50]. The goal of metric MDS is to find a configuration of points in a multidimensional space such that the inter-point distances are related to the provided proximities by some transformation. If the proximity data were measured without error in a Euclidean space, then classical metric MDS would exactly recreate the configuration of points. In practice, the technique tolerates error gracefully, due to the overdetermined nature of the solution.

Let p_{ij} refer to the proximity measure between objects i and j. The Euclidean distance between two points $X_i = (x_{i1}, x_{i2}, \ldots, x_{im})$ and $X_j = (x_{j1}, x_{j2}, \ldots, x_{jm})$ in a m-dimensional space is

$$d_{ij} = \sqrt{\sum_{k=1}^{m} (x_{ik} - x_{jk})^2} \tag{3.4}$$

When the geometrical model fits the proximity data perfectly, the Euclidean distances are related to the proximities by a transformation $d_{ij} = f(p_{ij})$. In classical metric MDS, a linear transformation model is assumed, i.e., $d_{ij} = a + bp_{ij}$. The distance D are determined so that they are as close to the proximities P as possible. There are a variety of ways to define "close". A common on is a least-squares definition, which is used by classical metric MDS. In this case, we define

$$I(P) = D + E \tag{3.5}$$

where $I(P)$ is a linear transformation of the proximities, and E is a matrix of errors (residuals). Since D is a function of the coordinates X, the goal of classical metric MDS is to calculate the X such that the sum of squares of E is minimized, subject to suitable normalization of X.

In classical metric MDS, P is shifted to the centre and coordinates X can be computed from the double centred P through singular value decomposition (SVD). For an $n \times n$ P matrix for n points and m dimensions of each point, it can be shown that

$$-\frac{1}{2}(P_{ij}^2 - \frac{1}{n}\sum_{j=1}^{n} P_{ij}^2 - \frac{1}{n}\sum_{i=1}^{n} P_{ij}^2 + \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}^2) = \sum_{k=1}^{m} x_{ik}x_{jk} \tag{3.6}$$

The double centered matrix on the left hand side (call it B) is symmetric and positive semidefinite. Performing SVD on B gives us $B = VAV$. The coordinate matrix becomes $X = VA^{\frac{1}{2}}$.

Retaining the first r largest eigenvalues and eigenvectors ($r < m$) leads to a solution in lower dimension. This implies that the summation over k in Equ.3.6 runs from 1 to r instead of m. This is the best low-rank approximation in the least-squares sense.

The algorithm consists of three steps:

1. Compute shortest paths between all pairs of nodes in the region of consideration. The shortest path distances are used to construct the distance matrix for MDS.

2. Apply classical MDS to the distance matrix, retaining the first 2 (or 3) largest eigenvalues and eigenvectors to construct a 2-D (or 3-D) relative map.

3. Given sufficient anchor nodes (3 or more for 2D, 4 or more for 3D), transform the relative map to an absolute map based on the absolute positions of anchors.

Chapter 4

Practical work and simulation results

4.1 Simulation of Range-based algorithms

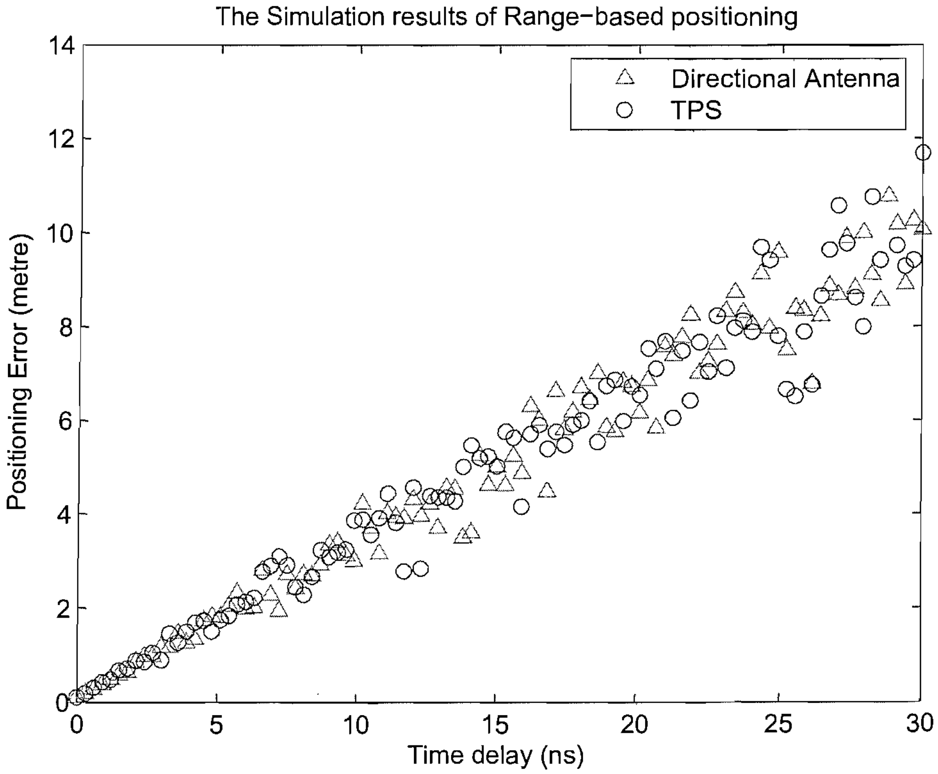


FIGURE 4.1: The Simulation results of Directional Antenna Scheme and TPS

As the presentation of TDS and Directional antenna Scheme in Section.2.2.2, both of which are range-based and passive algorithms with the minimum requirement of three beacon nodes for positioning. The unknown node only needs to be in the area where it can get the reception from all beacon nodes.

In the simulation, BN-1, BN-2 and BN-3 are representing the beacon nodes. In order to reduce the redundant geometrical calculation, we locate them at (0,0), (500,0) and (500,500) , as shown in Fig.2.6(a). The actual location of the unknown node is at (360,70), which can be chosen anywhere within the beacon signal coverage. We also introduce the error estimations of time at the BN-2, BN-3 and SN by increasing Gaussian random process with the range from $0ns$ to $30ns$. By repeating the experiment at each error level 100 times, we derive the performance of time error vs. positioning error, shown in Fig.4.1.

Generally, two simulation results looks similar. 3.3ns time estimation error would cause about 1 metre positioning error. These schemes must rely on high precise counters at all sensor nodes, which increase the energy consumption and costs for the network. Another crucial factor is that the time error of directional antenna scheme could be generated by the unstable beamwidth of DF and the different speed of mechanical antenna rotation. It would be hard to avoid. As we said in preview chapter, the range-based positioning algorithms are still not ready to apply on every single nodes, but it might be suitable for the higher level landmarkers and the less number of beacon nodes.

4.2 Simulation of Range-free algorithms

Before simulating distributed range-free algorithms in detail, we first outline the context in which these algorithms have to operate. The first consideration is that the requirement for sensor networks to be self-organizing implies that it is loosely-coupled of the placement of the sensor nodes when the network is installed, for example,they may be spread from plane. Consequently, we assume that nodes are randomly distributed across the environment. Our network layer supports localized broadcast only, and messages are delivered at the neighbours within a fixed radio range from the sending node. And we do not consider message corruption, that means all messages are delivered.

At the start of a simulation, we generate a random network topology (such as Fig.4.2), according to some parameters (number of nodes, number of beacon nodes, transmission range, etc.) The nodes are randomly placed in a 2-D square area with selected beacon nodes. The connectivity (average number of neighbours) is controlled by specifying the radio range and the density of nodes in the area. To account for the randomness in generating topologies, we repeated the simulation of each number of nodes 100 times with different distribution. For easy comparison between different scenarios, distance errors and position errors are normalized to the length of distribution area.

Fig.4.2 shows an standard scenario, in which contained 100 nodes with random distribution in 10 × 10 area. The radio range is set to 2.5, resulting in an average connectivity of about 15. In the simulation, we vary the connectivity with different number of nodes (from 50 to 200), and also for further comparison the number of beacon nodes(BNs) will be increased from the least number 3 to 10% of all nodes. The rest of parameters will not be changed, unless specified.

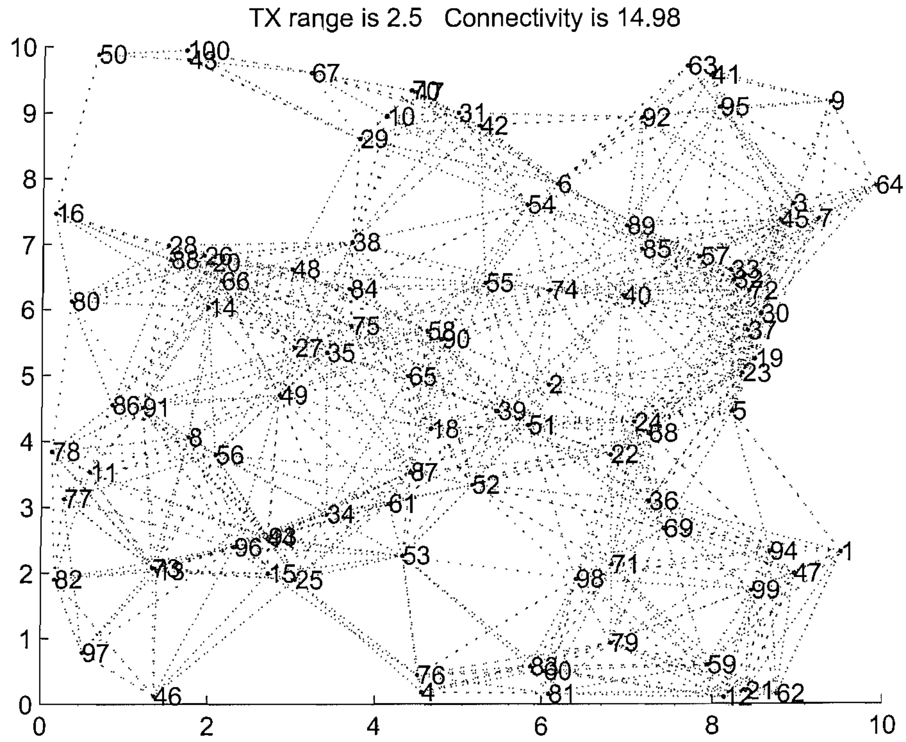


FIGURE 4.2: The example of network topology with 100 nodes

In order to study the impact of error on each step and derive the optimal combination for localization, we choose three distance measurement schemes (Count-hops, DV-hops and Smooth algorithm) as distribution in Section 3.5.1 to simulate and compare, and apply the best one with three different positioning estimation schemes (Lateration, Min-Max and MDS, see Section 3.5.2). By comparing the mean square error of each experiment, we obtain the following results.

4.2.1 Distance measurement

Fig.4.3 shows the comparison of three distance measurement methods. The mean of distance errors relate to the connectivity (or the density of nodes) in the network. We now discuss the sensitivity of each method.

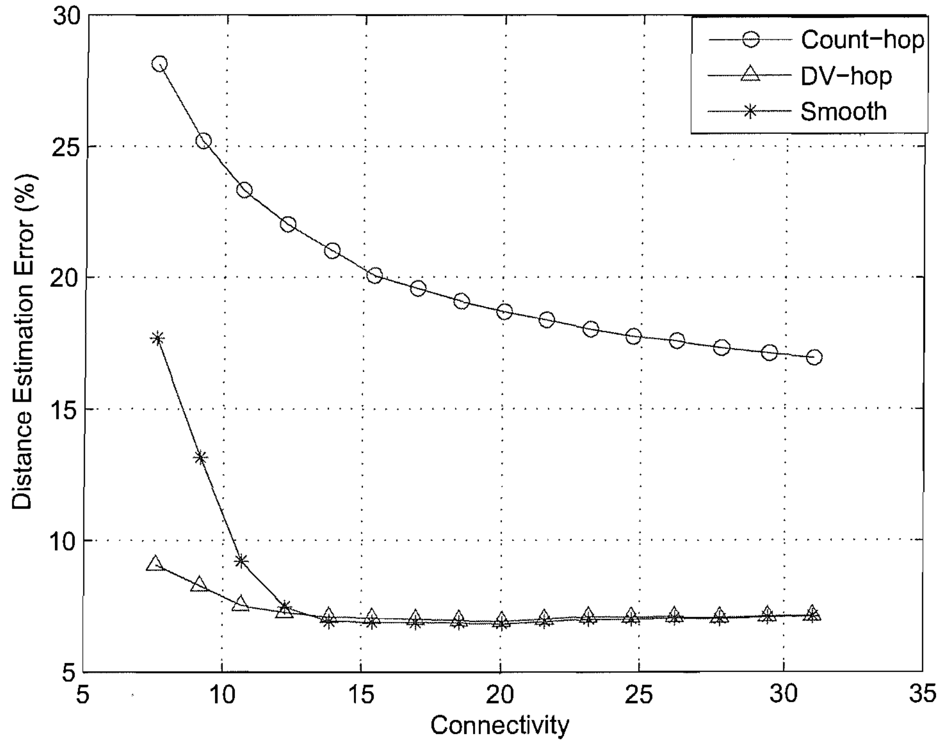


FIGURE 4.3: The comparison of distance measurement methods

4.2.1.1 Count-hops

Count-hops is the easiest way of the three methods. There are two opposite tendencies effecting the accuracy of Count-hop. First, without range errors the sum of the ranges along a multi-hop path will always be larger than the actual distance, leading to an overestimation of the distance. Second, the algorithm searches for the shortest path forcing it to select links that underestimate the actual distance when range errors are present. The combined effect shows non-intuitive results.

When the connectivity increased, more nodes can be available to create the shorter route and less hops from SN to BN. This leads to straighter pathes, and the accuracy would be improved as shown in Fig.4.3. However, the distance error is still too high ($> 15\%$) to accept even in a high density network (average connectivity > 30).

4.2.1.2 DV-hops

DV-hop method is a stable and predictable method. Since it does not use range measurements it is completely insensitive to this source of errors. Its performance shows in Fig.4.3 the low relative range error ($< 8\%$), when the connectivity's over 10. DV-hop searches for the path with the minimum number of hops, and times with the average hop distance, which is always shorter than radio range. From Fig.4.3, it shows that the accuracy can not get further improvement when the network density has reached a certain value (Connectivity is about 14).

4.2.1.3 Smooth algorithm

From the simulation result, the smooth algorithm does not show significant improvement as we expected. And it performs even worse than DV-hops, when the connectivity's less than 12. However it still has sightly better performance when the connectivity is from 13 to 20. If we can find out more suitable hop distance, the accuracy could be improved further.

Considering the range error, communication cost and computation, the DV-hop method is the best choice of the three methods. Now we start to investigate position estimation methods.

4.2.2 Position estimation

To obtain insight into the fundamental behavior of the Lateration, Min-Max and MDS algorithms, we now report on some experiments with controlled distance errors and beacon nodes placement. Firstly we apply three BNs in the network

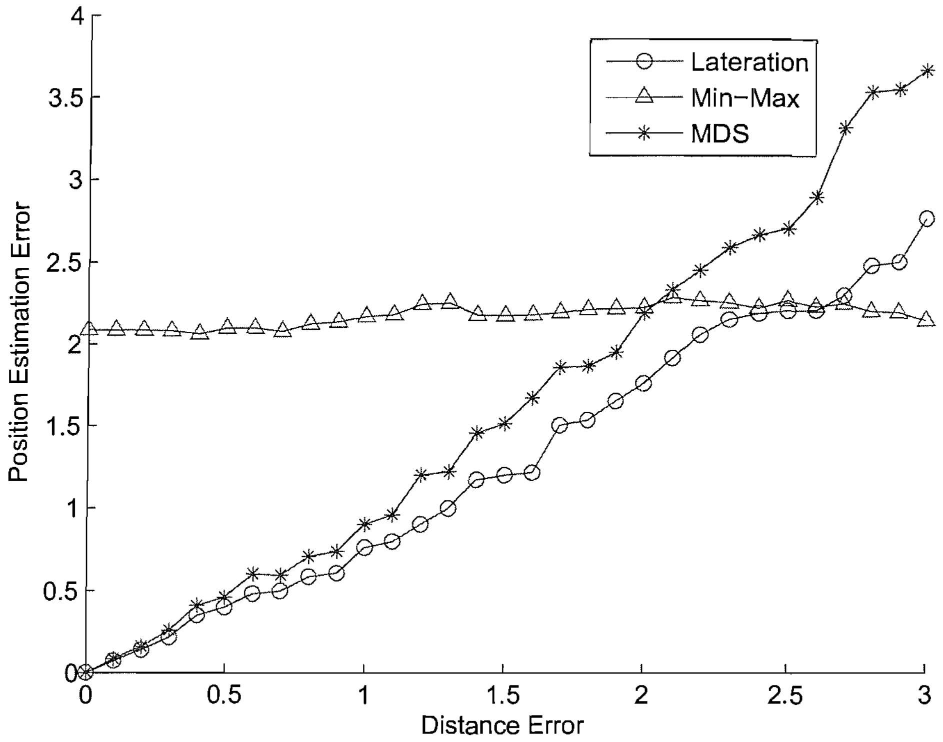


FIGURE 4.4: The impact of three positioning algorithms with range error

with only one SN. By increasing the range estimation error at all three BNs from 0 to 3, we derive different performance shown in Fig.4.4.

From the results, we easily find that the Lateration method gives the lowest positioning error. MDS shows the similar result as Lateration when the distance error is lower than 1. The worst performance's given by Min-Max method, since the intersection of three boundary boxes is not enough to converge to get a precise location even no range error occurred. Now we make a further test for these positioning algorithms with the selected distance measurement (DV-hop) in 100 different circumstances.

4.2.2.1 Lateration

As the assumption in Section.4.2, we increase the percentage of BNs in the network from 3 (the minimum requirement) to 10% of the total nodes. Fig.4.5 shows the combination results by lateration and DV-hop method. The positioning estimation error goes less than 10% only when the network connectivity is higher than 16, and over 10% nodes are BNs.

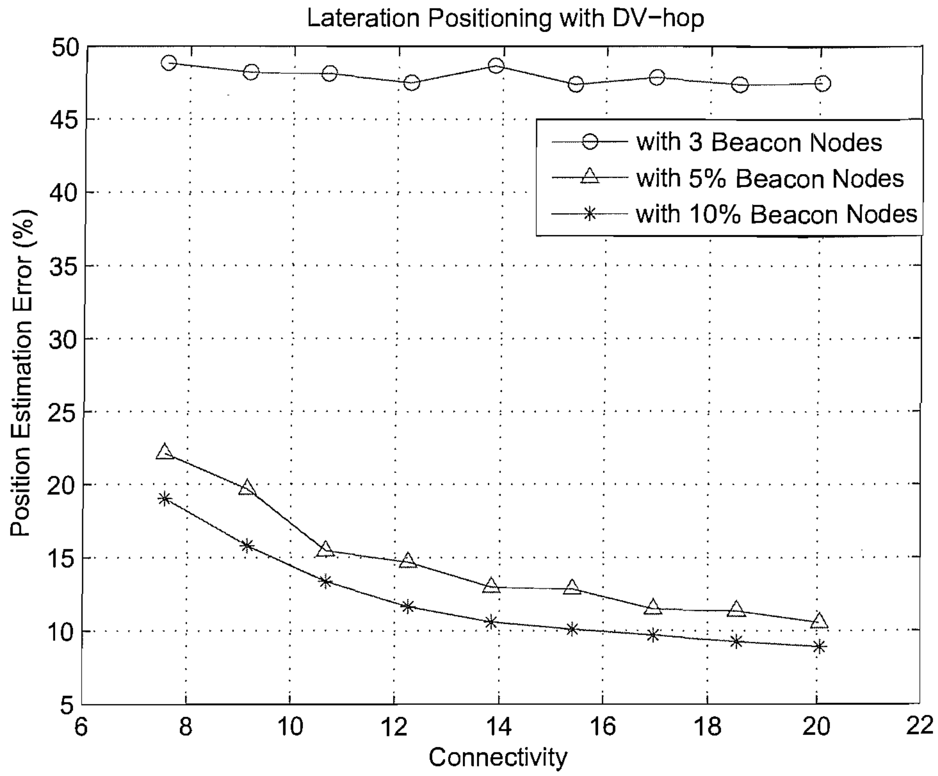


FIGURE 4.5: The performance of Lateration positioning algorithms with DV hops

4.2.2.2 Min-Max

Although Min-Max method has the consistent high error with three BNs, the performance's been improved rapidly by increase the density of BNs, the result shown in Fig.4.6. 16% positioning error can with 10% BNs is acceptable, by considering the its low computation.

4.2.2.3 MDS

The final result is generated by MDS and DV-hop, which is shown in Fig.4.7. Different from two results above, MDS method shows higher accurate, when the number BNs is at its minimum requirement. The more BNs leads to the accumulated error increased. However, there is another approach to using MDS with DV-hop. If we can divide BNs into several groups (or small map) in which only contains 3 BNs, we then derive one location by each group. By taking the mean value of these locations, the positioning accuracy would be increased.

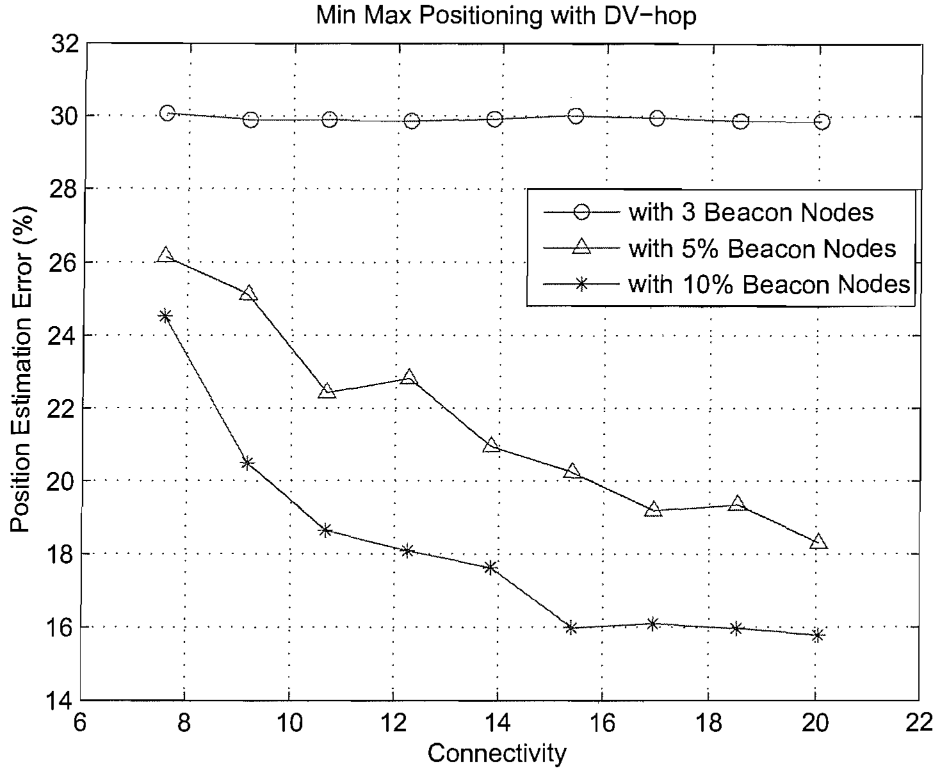


FIGURE 4.6: The performance of Min-Max positioning algorithms with DV hops

4.3 Computation

From above section, we knew that each positioning algorithm has their different advantages and disadvantages. Lateration gives the highest accuracy, Min-Max has lowest computation, and MDS provides higher accuracy with less BNs. Considering the performance of Lateration and Min-Max is similar, Hence, computation is another key factor. Here we list a table (Tab 4.1) which shows the float operation involved for calculation for each SN location.

Num of BNs	3	10	20	30
Addition (Lateration)	39	144	294	444
Addition (Min-Max)	20	76	156	236
Multiplication (Lateration)	54	180	360	560
Multiplication (Min-Max)	2	2	2	2

TABLE 4.1: The float operation involved in calculation for each SN position

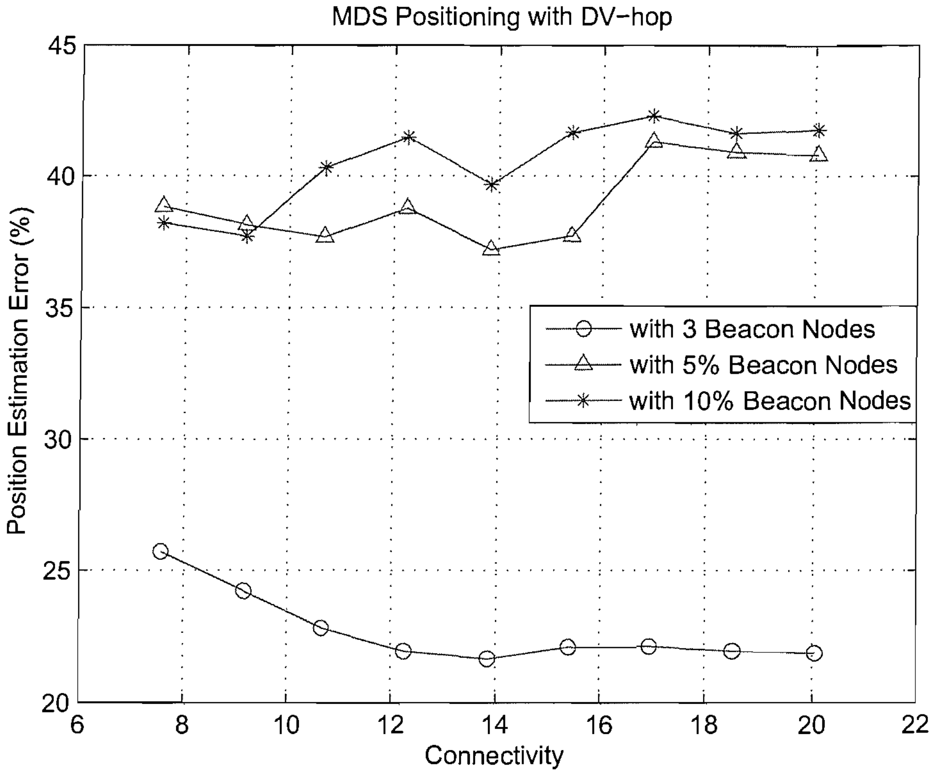


FIGURE 4.7: The performance of MDS positioning algorithms with DV hops

	Accuracy	Computation
Lateration	High	Low
Min-Max	High (only with the high density of BNs)	Very low
MDS	High (only with the low density of BNs)	High

TABLE 4.2: The comparison of three positioning schemes

From Table 4.1, we knew that the Min-Max method provides the superior advantage in computation over Lateration method. Hence, we derive the comparison of three positioning schemes in accuracy and computation (shown in Table 4.2). The Min-Max is the most efficient method in positioning if there're enough number of BNs.

Chapter 5

Conclusion and future work

5.1 Conclusion

Wireless sensor networks hold the promise for many new applications in the area of monitoring and control. It would be one of the key technologies in this century, and will be widely adopted in our life. The physical constraints and limitations of the sensor nodes still require more solutions. In this thesis, we addressed the issue of localization of outdoor WSNs. From the known localization algorithms, we prefer to use the methods with regular wireless module, easy installation, no or less additional hardware. In Range -based algorithm, we emphasized two inspired schemes as example to discuss, direction antenna scheme and TPS. However, we mainly focused on several range-free method to investigate, including Ad-hoc positioning, MDS, N-hop multilateration etc. Although some of the algorithm were developed independently, we found that they do share a similar structure, which usually is in 3 steps.

1. Determine the distances between unknowns and anchor nodes.

2. Derive for each node a position from its anchor distance.

3. Refine the node positions using information about the range, position and neighbour nodes.

The simulation results of positioning schemes showed that Lateration is capable of obtaining accurate positions, but also it's very sensitive to the accuracy and precision of the distance estimates. Min-Max is more robust, and easy to apply, especially reduced a lot of energy on computation. MDS is more suitable in a sparse BNs network, or to refine the positioning.

According to those results, we found that DV-hop/Lateration combination performs best (< 10% positioning error with 10% BNs) when there are no or poor distance estimates. DV-hop/Min-Max combination also provided acceptable results (< 15% positioning error with 10% BNs) using the least computation, and it would be improved by increasing the amount of BNs .

5.2 Future work

Regarding the future, we observed that the optimal hop distance for smooth algorithm could be the key factor to get further improvement, especially in 3D environment. Furthermore, additional simulation should involve physical effects, including multipath and interference. Monitoring and tracking dynamic nodes also have significant room to develop.

Bibliography

[1] A. Harter, A. Hopper, P. Steggles, A. Ward, and P. Webster, "The anatomy of a context-aware application," In Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking, Pages 59-68, Seattle, WA, Aug 1999.

[2] A. Smith, H. Balakrishnan, M. Goraczko, and N. Priyantha, "Tracking moving devices with the cricket location system," MobiSys'04, Boston, Massachusetts, USA, June 6-9, 2004.

[3] T. G. Zimmerman, "Wireless networked digital devices: A new paradigm for computing and communication."

[4] M. Satyanarayanan, "Pervasive computing: Vision and challenges, ieee personal communications," August, 2001.

[5] R. W. et al., "The parctab ubiquitous computing experiment," Tech. Report, XeroxPARC, 1995.

[6] A. Nasipuri and K. Li, "A directionality based location discovery scheme for wireless sensor networks," WSNA'02, Atlanta, Georgia, USA, Sep 28, 2002.

[7] X. Ji and H. Zha, "Robust sensor localization algorithm in wireless ad-hoc sensor networks," IEEE, 2003.

[8] N. Priyantha, A. Chakraborthy, and H. Balakrishnan, "The cricket location support system," In ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), August 2000.

[9] D. Niculescu and B. Nath, "Ad hoc positioning system(APS) using AOA," IEEE, 2003.

[10] X. C. . A. Thaeler, G. Xue, and D. Chen, "TPS: A time-based positioning scheme for outdoor wireless sensor networks," IEEE, 2004.

[11] R. Stoleru, T. He, J. A. Stankovic, and D. Luebke, "A high-accuracy, low-cost localization system for wireless sensor networks," SenSys'05, San Diego, CA, USA, Nov, 2005.

[12] D. Niculescu and B. Nath, "Ad-hoc positioing system," IEEE GlobeCom, Nov,2001.

[13] T. He, C. Huang, B. Blum, J. A. Stankovic, and T. F. Abdelzaher, "Range-free localization and its impact on large scale sensor networks," ACM Transactions on Embedded Computing Systems, Nov,2005.

[14] S. Meguerdichian, S. Slijepcevic, V. karayan, and M. Potkonjak, "Localized algorithms in wireless ad-hoc networks: Location discovery and sensor exposure," MobiHOC, Long Bench, CA, USA, 2001.

[15] L. Doherty, K. S. J.Pister, and L. E. Ghaoui, "Convex position estimation in wireless sensor networks," IEEE, 497 Cory Hall; Berkeley, CA 94720, 2001.

[16] D. Perkins and R. Tumati, "Reducing localization errors in sensor ad hoc networks," IEEE, 2004.

[17] Y. Shang, W. Rumi, and Y. Zhang, "Localization from mere connectivity," MobiHoc'03, Annapolois, Maryland, USA, Jun, 2003.

[18] A. Savvides, H. Park, and M. Srivastava, "The bits and flops of the n-hop multilateration primitive for node localization problems," In First ACM Int. Workshop on Wireless Sensor Networks and Application (WSNA), Sep,2002.

[19] S. Capkun, M. Hamdi, and J.-P. Hubaux, "GPS-free positioning in mobile ad-hoc networks," IEEE, 2001.

[20] A. Savvides, C. Han, and M. Srivastava, "Dynamic fine-grained localization in ad-hoc networks of sensors," ACM, 2001.

[21] L. Lazos and R. Poovendran, "Robust localization for wireless sensor networks," ACM Transactions on Sensor, Aug, 2005.

[22] R. T. Collins, A. J. Lipton, H. Fujiyoshi, and T. Kanade, "Algorithms for cooperative multisensor surveillance," In Proceedings of the IEEE, 89(10):1456-1477, 2001.

[23] B. Karp and K. H. T, "GPRS: Greedy perimeter stateless routing for wireless networks," In ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), pages 243-254, August 2000.

[24] J. Heidemann, "Using geospatial information in sensor networks," In ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), August 2000.

[25] P. Bahl and V. Padmanabhan, "RADAR: An in-building RF-based user location and tracking system," In Proceeding of INFOCOM, pages 775-784, March 2000.

[26] N. Bulusu, J. heidemann, and D. Estrin, "GPS-less low cost outdoor localization for very small devices," IEEE Personal Communications Magazine, pages 28-34, October, 2000.

[27] A. Ward, A. Jones, and A. Hopper, "A new location technique for the active office," IEEE Personal Communications, 4(5):42-47, October, 1997.

[28] M. Singh and V. K. Prasanna, "Energy-optimal and energy-balanced sorting in a single-hop wireless sensor network," In Proceeding s of the First IEEE International Conference on Pervasive Computing and Communications (PerCom' 03), 2003.

[29] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," ACM Transactions on Information System, 10(1):91-102, Jan 1992.

[30] F. H. Raab, E. Blood, T. O. Steiner, and H. R. Jones, "Magnetic position and orientation tracking system," IEEE Transactions on Aerospace and Eletronic Systems, 15(5):709-717, Sep 1979.

[31] http://www.directionsmag.com/press.releases/index.php?duty=Show&id=383.

[32] J. Hightower, G. Boriello, and R. Want, "An indoor 3D location sensing technology based on rf signal strength," Technical report, Seattle, University of Washington, 2000.

[33] G. Welch, G. Bishop, L. Vicci, S. Brumback, K. keller, and D. Colucci, "The hiBall tracker: High-performance wide-area tracking for virtual and augmented environments," ACM, 1999.

[34] R. Want, B. Schilit, N. Adams, K. P. R. Gold, D. G. J. Ellis, and M. Weiser, "An overview of the parc tab ubiquitous computing experiment," IEEE personal communications, 1995.

[35] R. Orr and G. Abowd, "The smart floor: A mechanism for natural user identification and tracking," Conf. on Human Factors in Computing Systems, 2000.

[36] A. Pentland, "Machine understanding of human action." In Proc. of the 7th Intĺ forum on Frontier of Telecommunication Technology, 1995.

[37] http://www.pinpointco.com.

[38] http://www.widata.com/solution_main.html.

[39] http://en.wikipedia.org/wiki/GPS.

[40] J. Hightower, "The location stack," Ph.D. thesis, University of Washington, 2004.

[41] A. Harter and A. Hopper, "A distributed location system for the active office," In IEEE Network, pages 62-70, Jan/Feb 1994.

[42] P. Bahl and V. N. Padmanabhan, "Enhancements to the RADAR user location and tracking system," technical report, Microsoft Research, Feb, 2000.

[43] J. Werb and C. Lanzl, "Designing a positioning system for finding things and people indoors," IEEE Spectrum, Sep 1998.

[44] "Smartdust chip with integrated RF communications," http://www.jlhlabs.com/jhill_cs/spec/, 2001.

[45] K. Whitehous and D. Culler, "A robustness analysis of multi-hop range-based localization approximations," IPSN06, Tennessee, USA, April, 2006.

[46] J. Hightower and G. Borriello, "Location sensing techniques," a technical report, 8th August, 2001.

[47] K. J. Krizman, T. E. Biedka, and T. S. Rappaport, "Wireless position location: Fundamentals, implementation strategies, and sources of error," IEEE, 1997.

[48] A.Savarese, K. Langendoen, and J. Rabaey, "Robust positioning algorithms for distributed ad-hoc wireless sensor networks," In USENIX technical annual conference, Monterey, CA, June, 2002.

[49] I. Borg and P. Groenen, "Modern multidimensional scaling, theory and applications," Springer-Verlag, New York, 1997.

[50] W. S. Torgeson, "Multidimensional scaling of similarity," Psychometrika, 1965.