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DISTANCE-BASED SENSOR NODE LOCALIZATION BY USING ULTRASOUND, RSSI AND ULTRA-WIDEBAND

— A COMPARISON BETWEEN THE TECHNIQUES

Master's thesis for the degree of Master of Science in Technology submitted for inspection in Vaasa, 15 of June, 2010.

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ABSTRACT:

Wireless sensor networks (WSNs) have become one of the most important topics in wireless communication during the last decade. In a wireless sensor system, sensors are spread over a region to build a sensor network and the sensors in a region co-operate to each other to sense, process, filter and routing.

Sensor Positioning is a fundamental and crucial issue for sensor network operation and management. WSNs have so many applications in different areas such as health-care, monitoring and control, rescuing and military; they all depend on nodes being able to accurately determine their locations.

This master's thesis is focused on distance-based sensor node localization techniques; Received signal strength indicator, ultrasound and ultra-wideband. Characteristics and factors which affect these distance estimation techniques are analyzed theoretically and through simulation the quality of these techniques are compared in different scenarios.

MDS, a centralized algorithm is used for solving the coordinates. It is a set of data analysis techniques that display the structure of distance-like data as a geometrical picture. Centralized and distributed implementations of MDS are also discussed.

All simulations and computations in this thesis are done in Matlab. Virtual WSN is simulated on Sensorviz. Sensorviz is a simulation and visualization tool written by Andreas Savvides.

KEYWORDS: Received signal strength indicator, ultrasound, ultra-wideband, MDS.

ABBREVIATIONS

2D	TWO DIMENSIONAL
3D	THREE DIMENSIONAL
ADC	ANALOG TO DIGITAL CONVERTER
AOA	ANGLE OF ARRIVAL
AODV	AD-HOC ON-DEMAND DISTANCE VECTOR
CDS	CONNECTED DOMINATING SET
CMOS	COMPLEMENTARY METAL–OXIDE–SEMICONDUCTOR
CSMA/CA	CARRIER SENSE MULTIPLE ACCESS/COLLISION AVOIDANCE
DOI	DEGREE OF IRREGULARITY
DSP	DIGITAL SIGNAL PROCESSING
DSR	DYNAMIC SOURCE ROUTING
DV	DISTANCE VECTOR
FCC	FEDERAL COMMUNICATIONS COMMISSION
FoM	FIGURE OF MERIT
GF	GRAPHIC FORWARDING
GPS	GLOBAL POSITIONING SYSTEM
IEEE	INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEER
LOS	LINE OF SIGHT
LQI	LINK QUALITY INDICATOR
MCU	MICRO-CONTROLLER UNIT
MDS	MULTI-DIMENSIONAL SCALING
MEMS	MICRO-ELECTRO-MECHANICAL SYSTEMS
MHT	MULTI-HYPOTHESIS TRACKING
MPCS	MULTI-PATH COMPONENTS
MT	MOBILE TERMINAL
MUI	MULTI-USER INTERFACE

NDT	NON-DESTRUCTIVE TESTING
NLOS	NON-LINE OF SIGHT
PHY	PHYSICAL LAYER
PRR	PACKET RECEPTION RATE
QOS	QUALITY OF SERVICE
RDEV	RANGING DEVICE
RF	RADIO FREQUENCY
RFRAME	RANGING FRAME
RSS	RECEIVED SIGNAL STRENGTH
RSSI	RECEIVED SIGNAL STRENGTH INDICATOR
RTT	ROUND TRIP TIME
RX	RECEIVER
SDP	SEMI-DEFINITE PROGRAM
SVD	SINGULAR VALUE DECOMPOSITION
TDOA	TIME DIFFERENCE OF ARRIVAL
TG	TASK GROUP
TOA	TIME OF ARRIVAL
TOF	TIME OF FLIGHT
TW-TOA	TWO WAY - TIME OF ARRIVAL
TX	TRANSMITTER
USB	UNIVERSAL SERIAL BUS
UWB	ULTRA-WIDEBAND
WG	WORKING GROUP
WPAN	WIRELESS PERSONAL AREA NETWORK
WSN	WIRELESS SENSOR NETWORK
WSNS	WIRELESS SENSOR NETWORKS

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CHAPTER 1

INTRODUCTION

The increase in miniaturization of RF devices and micro-electro-mechanical systems (MEMS) and the advances in wireless technologies have generated a great deal of research interest in the area of wireless sensor networks (WSNs). WSNs employ a large number of miniature autonomous devices known as sensor nodes to form the network without the aid of any established infrastructure. Figure 1 shows a simple wireless sensor network. In a wireless sensor system, each node is a small computing device, which has the capability to sense their environment, compute the information locally and ability to communicate with other nodes (MICROWAVES & RF 2005).

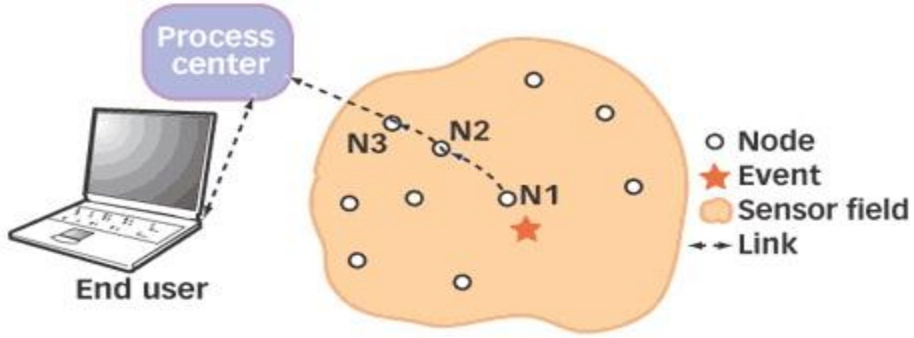


Figure 1. A simple wireless sensor network (WSN) (MICROWAVES & RF 2005).

WSNs use ad hoc topology because it is easy to deploy and decrease the dependence on infrastructure. The performance of a WSN mainly depends on the characteristics of the sensor node. Figure 2 depicts the system level architecture of a WSN. The node subsystem consists of a sensor or sensors for sensing, micro-controller unit (MCU) for computing and controlling the signals from the sensors, power supply for providing the supply voltage, the radio frequency

(RF) transceiver for transmitting and receiving signals and antenna for interference with the physical environment (MICROWAVES & RF 2005).

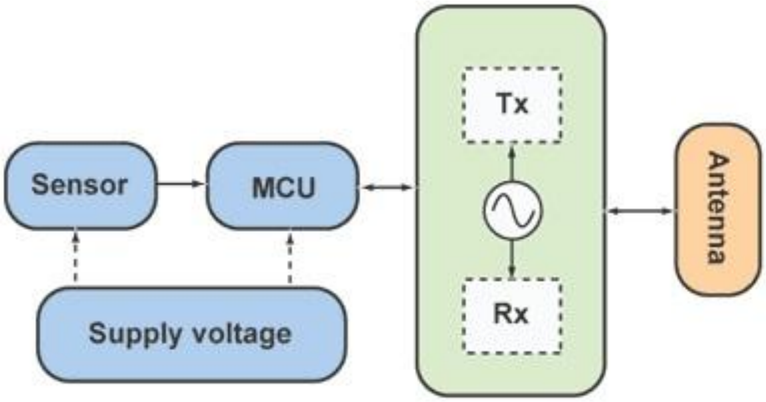


Figure 2. Wireless sensor node architecture (MICROWAVES & RF 2005).

Robust localization is a valuable tool for the development of low-cost sensor networks for use in location-aware applications and widespread networking. The sensed data are meaningless if we do not know where the data are from. Therefore, knowing the positions of sensor nodes is essential in wireless sensor networks. Reliable position information is needed in wide interest of applications such as security, medical, civil and environmental, tracking, autonomous robot navigation, industrial automation and home / building automation (Tulabandula 2007).

Thesis outline

In chapter 2 localization methods in WSN and classification of algorithms are presented. In chapter 3 distance-based sensor localization techniques: Received signal strength indicator, ultrasound and ultra-wide band; with their positives, negatives and applications are discussed. Sources of inaccuracy which influence the measurement are also presented in this chapter.

Chapter 4 is about multi-dimensional scaling and its implementations: Centralized and distributed. Simulations and results are in chapter 5 and chapter 6 is the concluding part of the thesis.

CHAPTER 2

LOCALIZATION METHODS IN WIRELESS SENSOR NETWORK

Localization in wireless sensor networks is about knowing the location of any network node at any time. Location information is essential for routing, tracking, inventory management, power management and other services. A localization service enables sensor nodes to drive their spatial coordinates without having to program and deploy each sensor to a precise location (Zhang & Herman 2006). Mobile sensor nodes are only controlled if the knowledge of their location is known. Many applications of WSN require good localization and synchronization.

2.1 Localization using GPS

Localization systems for WSNs can be based on the Global Positioning System (GPS). It is a satellite-based localization infrastructure. At any location on earth, a GPS-receiver can be localized using information of at least four GPS-satellites (Vandenbussche 2005). Generally it gives an accuracy of a meter (Zàruba, Huber, Kamangar & Chlamtac 2006). GPS can easily be used in sensor networks, by equipping the sensor nodes with GPS-receivers. But GPS-receiver consumes a lot of energy, which is known to be a scarce resource on a sensor node. According to Zàruba et al (2006), it is not feasible for indoor environment or such outdoor environment where line of sight is blocked by dense tree foliage or high buildings. GPS is an expensive method as to equip all nodes in a network with expensive GPS-receivers.

2.2 Localization using infrared

In WSN, localization can also be acquired by equipping the sensor nodes with infrared sensors (Vandenbussche 2005). Anchor nodes of the network are equipped with infrared receivers. When any unknown node sends an infrared signal at regular intervals, the signal is detected by special anchors (equipped with infrared receivers). The sender’s position can be estimated depending on the knowledge given by anchors. This method gives good accuracy at room level. This is suitable for both indoor and out door but for short ranges. Disadvantage of the method is the inaccuracy caused by multipath effects and line-of-sight requirements (Vandenbussche 2005).

2.3 Localization using sound

Localization in WSN is also possible with sound. Ultrasound is similar to sound except for its frequency, which is above 20 kilo-hertz (kHz) . Usually frequency of approximately 40 kHz is used for distance estimation (Tavakolizadeh 2007). Sensor nodes equipped with sound transceivers are used to handle ultrasound signals. Ultrasound is mainly used for short (3 meters to 10 meters) and very accurate ranging, with errors reported well below 10 centimeters (cm), even better accuracy is possible by using multiple receivers or emitters. Ultrasound signals are completely reflected or absorbed by walls, doors and windows, due to the large acoustic impedances differences between air and solid materials (Mayrhofer & Gellersen 2007). Ultrasound typically uses Time of Arrival (ToA) or Round Trip Time (RTT) algorithm between an unknown node and an anchor for ranging. Time Difference of Arrival (TDoA) is another approach for distance estimation where RF and ultrasound signals, both travels at different speeds, are sent simultaneously to the receiver. The ultrasound signal reaches at the receiver with a time difference from RF because light travels faster than sound. This difference in arrival time between the two signals is then computed at the receiver (Vandenbussche 2005).

2.4 Radio-based localization

Localization in sensor networks can be achieved using knowledge about the radio signal behavior and the reception characteristics between two different sensor nodes (Vandenbussche 2005). The information of strength of radio signal at the reception time is known as received signal strength indicator (or RSSI). It uses same radio hardware for both communication and localization. It does not require any additional sensor infrastructure. Therefore, it is cost, size and power efficient localization method (Zhang & Herman 2006). Real time localization information could be difficult with this method, due to the time taken by the RSSI in collecting more data to give high precision (Ohta, Sugano & Murata 2005).

2.5 Localization using ultra-wide band

Localization using ultra-wide band (UWB) is a range-based localization method. In UWB burst of RF of short duration (picoseconds to nanoseconds) are used to transmit data (Nekoogar, Dowla & Spiridon 2004). The UWB system can transmit the data in three wide ranges, which are 250 – 750 megahertz (MHz), 3.244 – 4.742 gigahertz (GHz), or 5.944 – 10. 234 GHz. In UWB, two way time-of-arrival (TW-TOA) can be used for ranging (Sahinoglu & Gezici 2006). The main sources of ranging errors in UWB ranging systems are multipath propagation, non-line-of-sight (NLOS) propagation and multi-user interference (MUI) (Gezici, Tian, Biannakis, Kobayashi, Molisch, Poor & Sahinoglu 2005). It is capable of providing highly accurate ranging in the harshest environments. UWB is useful in short range, high data rate, robust and low power communications. It is not confined to line-of-sight (LOS) communication so it can be used for both indoor and out door environments. It can also propagate through obstacles.

A short overview of main characteristics of localization methods in WSN is given in Table 1. This table is taken from (Vandenbussche 2005) and the author of this thesis has contributed in this table. From the table, it is concluded that RSSI is able to provide the cheapest localization system, while the form factor of the sensor nodes is not increased. UWB is a good choice for applications where high accuracy, low power communication, limited size and low cost are required. Ultrasound performs better for short range as compared to infrared but size, cost and power consumptions are main constrains in WSN applications.

Table 1. A short overview of the main characteristics of the localization methods in WSN.

	GPS	Infrared	Ultrasound	RSSI	UWB
Application indoors	Not recommended	yes	yes	yes	yes
Need for extra hardware	yes	yes	yes	no	yes
Cost of extra hardware	high	low	high	Not applicable	low
Size of extra hardware	average	average	large	Not applicable	average
Average expected error	± 10 meters	± 5 meters	± 10 centimeters	1 to 3 meters	± 15 centimeters

2.6 Classification of localization algorithms

The algorithms for sensors network should be robust and stable as sensor nodes are very prone to failures. The algorithms should work in case of node failure. Following are the broad classifications of localization algorithms.

2.6.1 Relative versus absolute

Relative localization algorithms estimate relative position of the nodes. In this algorithm, a group of nodes chose the coordinate system and is different from the original. It does not require any anchor nodes. In location aided routing applications, relative positions are just sufficient than calculating the absolute positions.

On the other hand, absolute localization algorithms locate absolute positions of node with the help of anchor nodes which broadcast their location information to the unknown nodes. The accuracy of the algorithm is proportional to the number of anchor nodes (Tulabandula 2007).

2.6.2 Centralized versus distributed

Centralized algorithms are designed to run on a central base station. Sensor nodes gather data and send all the node measuring quantities to base station for analysis, after which the calculated positions either relative or absolute are transported back into the network (Tulabandula 2007). Semi-definite Programming (SDP) and multi-dimensional Scaling (MDS) are examples of centralized localization algorithms.

In contrast, distributed localization algorithms are designed to run in the network, every node is responsible for computing its position. Bachrach and Taylor (2005), have discussed distributed algorithms in detail.

Range versus range free

Localization algorithms can be broadly classified into 2 categories: range-based algorithms and range free algorithms.

In range-based algorithms fine-grained information such as the distance between node pairs is used to compute the location of node. This distance information is obtained from,

- Time difference of arrival (TDoA) is used to calculate the distance between two nodes.
- Received signal strength information infers the distance between the receiver and the reference point: the information of signal strength at the reception.

- Time-of-flight (ToF) or the signal propagation time or time information of the communication signal is used to measure distance between the receiver and the reference point.
- Angle of arrival (AoA) method uses the direction at which the signals are received at the reference point in some reference frame.

On the other hand, range free algorithms infer coarse grained information such as proximity to a reference point to drive node's positions in the global network. Inherently, these algorithms give limited precision. They do not require any additional hardware and most require only simple operations (Peng & Sichitiu 2005).

CHAPTER 3

DISTANCE-BASED SENSOR NODE LOCALIZATION

3.1 Distance estimation techniques

Considering hardware capabilities, available localization methods can be distinguished into two classes: connectivity-based (also called range-free) and distance-based (also called range-based). Connectivity-based algorithms use only the contents of the received messages to locate the entire sensor network. Connectivity-based methods are cost effective but their performance is usually worse. Distance-based techniques use inter-sensor distance or angle measurements in location calculation. Distance-based algorithms give good estimation of location though they require additional equipment (Niewiadomska-Szynkiewicz & Marks 2009).

This thesis is mainly focused on distance-based sensor node localization and the distance estimation techniques which are discussed and used for comparing the accuracy between the techniques are: Received signal strength indicator, ultrasound and ultra-wideband.

3.1.1 Received signal strength indicator

Localization technique based on the information of strength of radio signal at the reception time is known as received signal strength indicator (or RSSI). RSSI is an arbitrary integer value corresponding to the power strength of the received packets measured by the wireless card (Peng & Sichitiu 2005). The higher the RSSI value, the better the signal reception (Vandenbussche 2005). RSSI is suitable for coarse-grained localization (approximately 10 meters-30 meters in 802.15.4 and 802.11 networks). RSSI has a fair edge from other localization techniques because it eliminates the requirement of additional hardware in small wireless devices and shows good characteristic with respect to size, cost and power consumption. RSSI is attenuated by large-scale path losses, frequency selective fading and shadowing losses (Patwari & Hero Iii 2003). There are two common localization techniques which use radio signal strength information (Vandenbussche 2005):

1. **Converting Signal Strength to Distance:** Anchors send their position at regular intervals and unknown nodes measure the strength of received signal. The received signal strength is then converted to distance estimation by using exponential relation between the transmitted signal strength and the distance the signal has travelled. Afterwards, this distance estimation information is used to calculate coordinates between anchor and unknown nodes with the help of trilateration.

   Indoor errors of this method are larger than outdoor errors, at average of around two to three meters. The affecting factors which cause errors are fading, reflections, shadowing and multipath propagation.
2. **Fingerprinting Signal Strengths:** This is an anchor based technique that consists of two separate phases:
   - Offline phase: Fingerprint database of the environment is constructed in this phase.
   - Online phase: In this phase, real time localization is performed.

   The main advantage of this method is that it handles the unpredictable variations of space. Thus, reduces the errors to an average of one to two meters.

Ranging

The RSSI ranging works as follows. A sensor node sends out a radio message with certain signal strength and one field of this message records the signal strength of sending. The receiver of this message can measure the signal strength of the received message. The original signal strength and received signal strength can be compared and the distance between the sender and receiver can be estimated.

Following mathematical expression is used for calculating RSSI value as a function of distance between two nodes in free space (Clemmensen 2007):

$$Loss(d) = 10.log_{10}\left((\frac{4\pi}{c}df)^2\right) \tag{3.1}$$

$$Loss(d) = 20.log_{10}(d) + 20.log_{10}(f) + 20.log_{10}\left(\frac{4\pi}{c}\right) \tag{3.2}$$

$$loss(d) = 20.log_{10}(d) + 20.log_{10}(f) - 147.55 \tag{3.3}$$

$$RSSI(d) = TS - Loss(d) \tag{3.4}$$

Where, d is the distance between nodes in meters, f is the frequency of the signal, TS is the transmission strength of the signal and c is the speed of light. Generally, RSSI is affected by several factors, such as (Awad, Frunzke & Dressler 2007; Clemmensen Jr 2007; Flammini, Marioli, Mazzoleni, Sisinni & Taroni 2006):

- Transmitter variability: Different transmitters behave differently even when they are placed at the same point.
- Receiver variability: Different receivers behave differently when all environmental conditions are same.
- Antenna orientation: Different antennas have their own radiation patterns.
- Multipath fading and shadowing in the RF channel: Channel behaves differently in different environment conditions.

In a noisy indoor environment an average positioning error of 50 cm on an area of 3.5 x 4.5 meters (m) is possible with RSSI if radio frequency and algorithm parameters are chosen wisely based on empirical studies (Awad et al 2007; LI 2007; PATWARI & HERO III 2003) have proposed some techniques to improve RSSI.

Applications

(Flammini et al 2006; Srinivasan & Levis 2006) have identified few applications of RSSI:

- RSSI can be used to estimate the quality of the link. IEEE 802.15.4 encourages its use to estimate wireless link quality.
- Measurement of noise floor is also possible with RSSI.

- RSSI technique is a good choice in coexistence schemas such as adaptive frequency hoping and listen-before-talk. IEEE 802.15.4 uses RSSI function to perform CSMA/CA.
- RSSI is often used as an on/off indicator for a busy channel.
- It is used as an indicator for packet reception rate (PRR) estimation. If there is a change in RSSI over time for a link then it shows that estimation of PRR may be not accurate (Srinivasan & Levis 2006).
- RSSI provides a very effective method of tuning radio receiver and it can be utilized as part of a carrier squelch circuit[1.]

Advantages

- Same radio hardware for both communication and localization. No need for additional hardware for sensor nodes.
- Ranging with this technique is very simple and cost efficient.
- No need for separate ranging message.
- It consumes little power for computation.

Srinivasan & Levis (2006) have mentioned some positives of RSSI like,

- Hardware miscalibartion can be low due to RSSI symmetry in links as insignificant in CC2420.
- It can be a good indicator of link quality if its value is above the sensitivity threshold.
- RSSI has very small variance compared to LQI (link quality indicator) for any link over time.
- It gives good early indication of poor reception conditions (DVB 2007).
- According to DVB, no need to demodulate a transport stream to estimate RSSI.

1. An electric circuit that cuts off a receiver when the signal becomes weaker than the noise.

Disadvantages

(DVB 2007; Ohta, Sugano & Murata 2005) have discussed following disadvantages of received signal strength indicator:

- It supplies an estimate for the energy available in the band but not the quality of the signal.
- Indication of bit or byte errors is not given and so does not provide deterministic QOS (quality of service) metrics.
- Distance estimation using RSSI alone can generate large errors due to fading channels.
- Real time localization information could be difficult due to the time taken by the RSSI in collecting more data to give high precision.
- RSSI distance prediction in 3D deployments is almost impossible.

3.1.2 Ultrasound

Localization is also possible by using sound signals. Ultrasound is reverberate sound pressure with a frequency above human hearing limits, that is approximately 20 kHz. Usually frequency of approximately 40 kHz is used for distance estimation. In general, ultrasound is used for ranging in fine-grained localization. Ultrasound sensors are used to handle ultrasound, which are equipped with ultrasound transceivers. Ultrasound transmitter consists of three blocks: The voltage generator, the ultrasound transducer and the control and configuration system. There are three blocks in ultrasound receiver as well: The ultrasound amplifier, the electronic compass and the control unit **(**Escudero, Margalef, Luengo, Alsina, Ribes & Pérez 2007).

Ultrasound usually operates at very low frequency bands (typically 40 kHz) but possesses a good precision for location sensing at a slow propagation speed of sound (340 m/seconds), which is markedly smaller than the speed of light, therefore, scheduling of sensor node introduces small delays that do not cause an error in distance estimation (Jang & Skibniewski 2007). Ultrasound is mainly used for short (3 m to 10 m) and very accurate ranging, with errors reported well below 10cm, even better accuracy is possible by using multiple receivers or emitters. Cricket and Active Bat are ultrasound based systems, give high precision of accuracy but Cricket requires very dense placement of beacon and line-of-sight beacon contact (Priyantha, Chakraborty & Balakrishnan 2000). Ultrasound signals are completely reflected or absorbed by walls, doors and windows, due to the large acoustic impedances differences between air and solid.

Ranging

Ultrasound typically uses ToA or RTT (Round Trip Time) algorithm between an unknown node and an anchor for ranging. Ultrasound sends a signal to a receiver and in return, the recipient sends a signal back to the transmitter, see Figure 3(a). Both receiver and transmitter use time stamp to measure signal arriving time (Vandenbussche 2005). Following equation is used for measuring ToA of ultrasound (Ilyas & Mahgoub 2005):

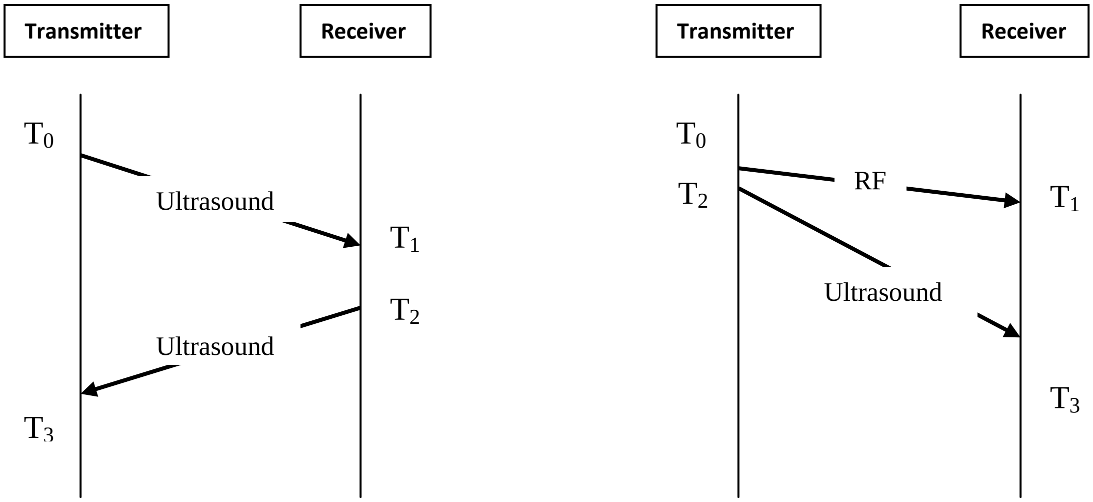
$$D = \frac{((T_3 - T_0) - (T_2 - T_1)) * V}{2} \tag{3.5}$$

Where, D is the distance between transmitter and receiver, V is the velocity of ultrasound signal. Error in this technique may come from delay to process the time of signal at receiver's side (T_2-T_1). Localization errors of tens of centimeters can be achieved from this algorithm.

TDoA is another approach for distance estimation where RF and ultrasound signals, both travels at different speeds, are sent simultaneously to the receiver, see Figure 3(b). The ultrasound signal reaches at the receiver with a time difference from RF because light travels faster than sound. This difference in arrival time between the two signals is then computed at the receiver.

$$D = ((T_3 - T_1) - (T_2 - T_0)) * \left(\frac{V_{RF} * V_{US}}{V_{RF} - V_{US}}\right) \tag{3.6}$$

Where, D is the distance between emitter and receiver, V_{RF} is the velocity of radio frequency and V_{US} is the velocity of ultrasound. According to Vandenbussche (2005) TDoA gives the accuracy of centimeters in ultrasound.



(a) (b)

Figure 3. (a) ToA measurements; (b) TDoA measurements.

Applications

- *Ranging:* Ultrasound is used for precise ranging between unknown node and an anchor.
- *Extension of acoustic location system:* The acoustic location system can also be extended to track clients quietly and robustly by using ultrasound that will make the system robust.
- *Non destructive testing (NDT):* Non destructive nature of ultrasound is playing an increasing role in testing the building intelligent predictive maintenance systems before failure.
- *Industrial usage:* Frequencies above 80 kHz are used to detect flaws in metals and in products. Ultrasound is also used in industry for thickness measurement, process control, plastic and metal welding, soldering, machining (see more in (Shoh 1975)).

- *Medicine and health:* High frequency pressure waves are used to investigate various organs of body and flaw detection in medicine. High-power ultrasound has been used with focusing arrangements to destroy deep-lying tissue in the body (TalkTalk).
- *Microscopes:* Extremely high frequencies of about 1000 MHz or more are used in ultrasonic microscopes.
- *Depth measurement:* Ultrasound echoes have been produced in order to measure the depth of the sea and to detect submarines.
- *Cleaning:* Ultrasound can also be used for cleaning. High vibration waves of ultrasound are passed which cause removal of dust particles.

Advantages

- Circuitry of ultrasound devices is simple and inexpensive as compared to sophisticated and costly circuitry of infrared devices.
- Ultrasound has very high precision accuracy of about 1 cm resolution of distance measurement.
- Attenuation and reflection caused by noise do not affect the ultrasound signals much due to robustness nature of ultrasound (Whitehouse, Karlof, Woo, Jiang & Culler 2005).
- Combination of radio frequency and ultrasound can increase convergence range, reduce the effect of multipath in radio signal propagation and decrease cost factor (Jang & Skibniewski 2007).

Disadvantages

- Extra hardware is required to do distance estimation or ranging in ultrasound such as ultrasound transducers and amplifier Circuitry (Jang & Skibniewski 2007).
- Use of ultrasound for ranging is an expensive technique due to its additional hardware as compared to other ranging techniques like RSS.
- Form factor or miniaturization of ultrasound device is a major concern for WSN.
- Additional power is required for transmitting and receiving signal amplification.

- Ultrasound can only be used for short ranges, which are around 3 m to 10 m. Therefore, ultrasound is mainly suitable in dense sensor networks.
- Environmental conditions (temperature, relative humidity and atmospheric pressure) affect the ultrasound's accuracy (Li 2007).
- Sound reverberating effects make ultrasound technique unsuitable for many applications (Li 2007).

3.1.3 Ultra-wide band

A sub group of IEEE 802 named Task Group (TG 4a) started developing a variation of IEEE 802.15.4 for an alternative physical layer (PHY) in 2004 based on IEEE 802.15 WG (working group). They developed an ultra-wide band (also known as UWB or as digital pulse wireless) based layer standard which had a precision ranging capability for short range networks (Chong, Watanabe & Inamura 2006). In UWB, burst of radio frequency of short duration (picoseconds to nanoseconds) are used to transmit data. Whereas, other wireless technologies use radio sine waves at specific frequency which results in a continuous transmission of data. That is why UWB sends more data than other technologies. The UWB system can transmit the data in three wide ranges, which are 250 – 750 MHz, 3.244 – 4.742 GHz, or 5.944 – 10. 234GHz. Thus, each radio channel can have a bandwidth of more than 500 MHz, depending on its center frequency.

UWB technology is simple in terms of complexity and consumes low power, as well as the power of the signal from UWB devices is allowed up to -41.3decibelmeters/MHz, which is quite low, but has the ability to carry signal through doors and other obstacles. Low power consumption is due to the strict power limits imposed by Federal Communications Commission (FCC). This restriction made possible to develop cost effective CMOS (Complementary metal–oxide–semiconductor) implementation of UWB radios. UWB became an ideal solution for accurate ranging (under a centimeter), low power, low cost, and very high data rates capable sensor nodes (Chong et al 2006; Intel 2004; Huang, Dutkiewicz, Gandia & Lowe 2006).

Ranging

RDEV (ranging device), the device capable of handling ranging according to IEEE 802.15.4a standard, provides optional ranging support. RFRAME (ranging frame), is indicated by setting a ranging bit in the physical layer (PHY) header of the IEEE 802.15.4a packet. An RDEV sends an RFRAME to the other RDEV with which it wants to determine the range. A reply RFRAME is then sent back. Thus, two way time-of-arrival can be used to determine the total elapsed time between the departure of RFRAME and the reception of reply RFRAME, as is shown in the equation below:

$$T_r = 2T_t + T_{ta} \qquad (3.7)$$

Where T_r is the total elapsed time of signal, Tt is the one way time of flight of the first arriving signal component and Tta is the turn round time, see Figure 4. The time of arrival is determined by the time-stamp packet transmitted by the recipient back to the sender. Time-stamp report contains ranging counter start value, ranging counter stop value, two numbers to characterize the crystals and FoM. The recipient of the time-stamp packet then sends back the acknowledgement (Sahinoglu & Gezici 2006).

The ranging accuracy depends on the accuracy of calculated two way time of flight. The main sources of ranging errors in UWB ranging systems are multipath propagation, NLOS propagation and multi-user interference (MUI).

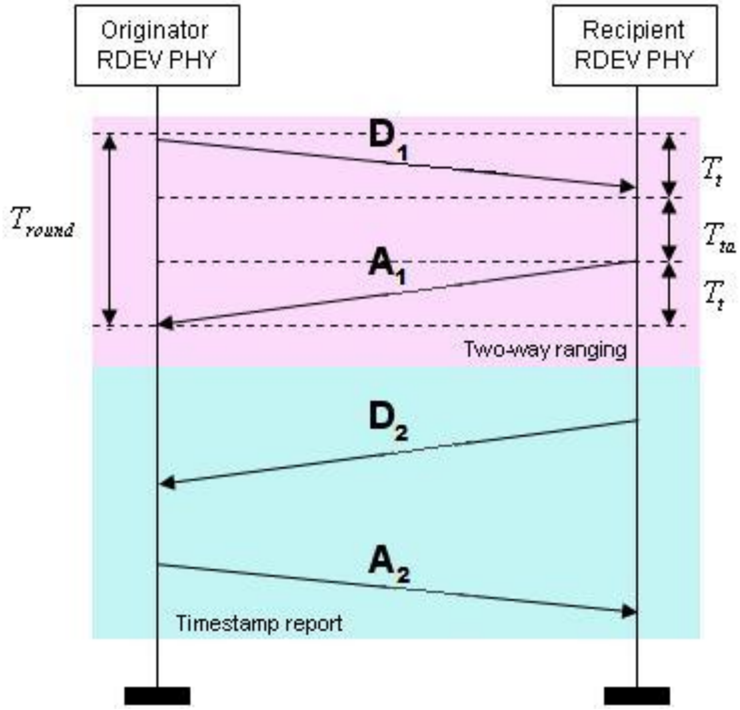


Figure 4. Message exchanges in two-way time of arrival based ranging.

There are three more techniques which can be used for distance estimation, namely; angle-of-arrival, time-difference-of-arrival, received-signal-strength indication:

AoA is the position determining technique which uses special antenna arrays to determine the angle of the arriving signal. This technique makes UWB very expense due to the use of antennas and inaccuracy in multipath.

TDoA requires high precision synchronization among reference nodes if there is no synchronization between a given node and reference node.

Distance can also be measured by analyzing the strength of the signal from transmitter to receiver. This is called received-signal-strength indication technique. To determine the signal strength the characteristics of the channel must be known.

Applications

UWB can be used in a variety of applications due to its capabilities of low power, low cost and no interference. Some of them are mentioned by Chong et al (2006) and Intel (2004), are as follows:

- UWB can enable rescuing or locating people, animals or objects could also be possible in situations where there are obstacles or weak signals like hunters in a dense forest, civilian in a burning building, hiker in a remote area or tracing a car in a large parking area.
- UWB can provide high level of security assurance on highways or deserted area if vehicles or MT's[2] (mobile terminal) are equipped with this technology. It will enable communication between them so that real time local intelligence could be provided to avoid any type of accident.
- UWB technology can also be used in military combat situations, especially in densely populated areas or cities. If every soldier is equipped with this technology, they can easily communicate with each other and arrange themselves according to the situation.
- Appliances integrated with UWB technology can provide location based and personalized services. The appliances can track the location of the person carrying the UWB technology enabled MT and provide services like switching on/off lights or personalized pc services (For example: automatic login to computers)
- Low power consumption property of UWB is ideal for mobile phones. A cell phone operating on UWB could be able to work for weeks without any need to recharge.
- Battery powered MT technology has a lot of constraints, for example that of power consumption and multi-path interference. Theses problems of ad-hoc networking can be solved using UWB technology as it can provide high data connectivity at remote locations with very low power consumption.

2. The technical term for a mobile phone (or handset) or other mobile communication devices.

- WPAN (wireless personal area network) based services can replace connectivity between consumer electronics and personal computers (PCs). For example devices such as camcorders, digital cameras, MP3 players, printers, scanners, external storage devices, Bluetooth enable devices and mobile phones can be connected without using any cables. Even the data transfer rate will be higher than current wired technologies such as USB 2.0.

Advantages

- *Speed:* UWB device is capable of high data transfer rate as compared to current network technologies, as well as it can also be used for low speed applications such as temperature reading.
- *Security:* UWB systems can provide higher level of security as they operate below the noise level, thus making them nearly undetectable (Chong et al 2006).
- *Accurate ranging:* UWB technologies are highly accurate (within centimeters resolution), thus providing location based services. Ultra wide band (UWB) time-of-flight based systems work both indoor and outdoor. Indoor they can achieve ranging precision better than 1m for ranges of up to 50m and positioning accuracy of up to 15cm. Outdoor the accuracy of UWB positioning and ranging systems can be also very high, approx. 1m for distances of up to 2 kilometers.
- *Lower cost and complex:* UWB technologies are not only cost effective in manufacturing but also consume less power. This means that their operating and maintenance costs are also very low.
- *Advantages over RF:* RF spectrum availability is becoming scarce. UWB can enable vast new spectrum availability (artimi 2006).
- *No line-of-sight:* UWB is not confined to line-of-sight communication. It can also propagate through obstacles.
- *Coexistence:* Artimi (2006) has mentioned that UWB signals do not interfere with conventional RF carriers thus it can coexists with RF technology as well as with multiple UWB appliances.

- *Fading robustness:* UWB systems can resolve multiple path components (MPCs) even in dense multipath environments as they are immune to multipath fading (Chong et al 2006).

Challenges

Before UWB can be used widely in a verity of appliances and applications, it has to overcome some technological and management based challenges. A few of those are mentioned by Chong et al (2006), Intel (2004) and Nekoogar et al (2004), they are listed below:

- Multipath propagation
- Non line of sight propagation
- Multiuser interference
- Interoperability
- Quality of service
- Global spectrum allocation
- Ease of product integration
- Overall cost effectiveness
- Long synchronization time
- Antenna size and design for MTs
- Problems of integrated circuit and digital signal processing (DSP). For example the need for high analog to digital converters (ADC) and high speed data rates.

3.2 Sources of inaccuracy

3.2.1 Network graph realization uniqueness

An important problem in distance based measurement of sensor networks is Sensor Network Localization, that is, whether a sensor network is uniquely localizable or not. The problem is that of determining the Euclidean coordinates of all the sensors on a planar or three dimensional array where a collection of inter sensor distances are known (via TDoA, RSSI, for example). Additionally, the Euclidean coordinates of beacon or anchor are also known (via GPS, for example) (Anderson, Belhumeur, Eren, Goldenberg, Morse, Whiteley & Yang 2006).

In graph theory, the problem of determining Euclidean position for the vertices of a graph is known as *the graph realization problem* (Moore, Leonard, Rus & Teller 2004). Consider a graph $G = (V, E)$ consists of n vertices and m edges and a set of non negative weights $\{d_{ij} : (i, j) \in E\}$ on its edges. Now try to assign coordinates to each vertex such that the Euclidean distance between any two adjacent vertices is or equal to the number associated with the edge. This is graph realization problem. In sensor networks scenario, the vertices of *G* correspond to sensors, the edges of *G* correspond to communication links and the weights correspond to distances. Sensor Network Localization problem can be observed as a variant of graph realization problem in which a subset of the vertices is constrained to be in certain positions (So & Ye 2004).

A *realization* of a graph *G* is a function of *p* that maps the vertices of *G* to points in Euclidean space. The combination of *G* (graph) and *p* (realization) is called a framework. The idea of point formation is basically the same as the concept of a framework in mathematics, mechanical or in civil engineering (Aspnes, Eren, Golderberg, Morse, Whiteley, Yang, Anderson & Belhumeur 2005). A framework that can be continuously deformed while preserving all constraints to produce an infinite number of different realizations is said to be non rigid or flexible, otherwise it is rigid or inflexible (Hendrickson 1992). A graph that has a unique realization (by translation, rotation or reflection) must be rigid but a rigid graph can be non unique, like the rigid framework in Figure 5 has two realizations in the plane. In rigid graph, there are two types of discontinuous deformations that can prevent realization from being unique, (i) flip ambiguities (ii) discontinuous flex ambiguities. Graph theory suggests ways of testing whether specific graph is corrupted by flip and flex ambiguities or has a unique realization (Moore et al 2004).

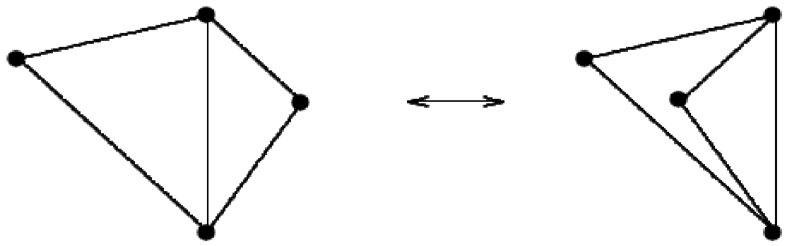


Figure 5. A graph with two realizations in the plane (Hendrickson 1992).

There are three different notions of rigidity:

1. Rigidity: non rigid graphs have a motion.
2. Infinitesimally rigid: non infinitesimally rigid graphs have initial velocity candidates.
3. Generically rigid: generic rigidity is a property of the graph not the embedding.

A formation that is exactly determined up to congruence by its graph and distance function is called globally rigid. Global rigidity is a particular graph property which is associated with unique localizability of the sensor networks. Condition for unique localizability of sensor network in d dimension is global rigidity, if three points in the plane do not lie on a line and four points in space do not lie in a plane then the points are said to be lied in a proper subspace not in general position (Aspnes et al 2005).

Unique graph realization problem of sensor networks have drawn a lot of attention from researchers. Therefore, many algorithms have been proposed but all algorithms have their stronger and weaker aspects to address this problem. There are still some questions related to graph realization are under consideration, such as:

- What are the precise conditions for unique localizability?
- What is the computational complexity of network localization?
- What is the complexity of network localization in typical network deployment scenarios?
- What are the rigidity algorithms in higher dimensions?

3.2.2 Geometry

- How to distribute sensors such that events are captured?
- How to localize events recorded on ad hoc sensor networks?
- How to predict future sampling requirements based on current data?
- How can a limited amount of strictly local information be used in order to achieve distributed information knowledge of global network properties?

All these above mentioned questions can be answered by making use of underlying geometry. Geometric approaches can address the problems at structural, functional and application levels in sensor networks through concepts and techniques.

Geometry plays a vital role in all aspects of the sensor network especially when network has to discover its own geometry.

Geometry in sensor network has high correlation with network topology. Topology of a network mainly depends and adapts to the transmission power of individual sensor. Topology control is needed to maintain network connectivity, optimize network lifetime and making it possible to design power efficient routing (Islam 2007). Topology control algorithms deal with finding a suitable structure (a spanning sub-graph) of the original graph which is expected to have certain features, like connectedness, planarity, sparseness and bound-degree.

Many considerable researches in geometric models and geometric understandings have been done but still there are some open problems and issues to be considered. Few of them are mentioned below (Suri, Wattenhofer & Widmayer 2007; Islam 2007):

- Unit disk model has been used very efficiently to derive many theoretical results for routing in sensor networks but there is lack of appropriate model which captures intricate reality of radio transmission.
- Not much existing work is done in the direction of data processing in the network and data storage that should be adaptive to the network geometry.

- Connected dominating sets (CDS) have proven to provide an important backbone in sensor networks.
- Finding a connected dominating set whose size is within a small constant factor of the minimum connected dominating set is still a challenging problem.
- Maintenance of CDS stability, in the face of frequent topology change, is another critical issue. There is a need for building robust CDS algorithms for sensor networks which deal with important issues like link's instability, node mobility, insertion of new nodes and consideration of node failure.

There are other challenges beside these above mentioned problems, that is, the discrete nature of sensor network. When existing tools and representations, which were developed for continuous domain, are migrated to discrete network then noise related issues arise. Thus, noise removal and robustness to link variations must be addressed (Gao 2008).

3.2.3 Noise

Localization of any object is essential task in sensor networks but taking the perfect measurements in all situations is not possible by any sensor. In practice, there are many factors which influence the location estimation and noise is one of them. Bayesian filter techniques provide a powerful tool which deals with uncertainty of measurements and perform multi sensor fusion (Fox, Hightower, Liao, Schulz & Borriello 2003).

Bayes filters probabilistically estimate a dynamic system's state from noisy observations where state is an object's or a person's location and it could be a 2D (dimensional) or 3D position. Bayes filters sequentially estimate the beliefs, at each point in time the uncertainty is represented by a probability distribution over the state at time t by random variables x_t called *belief Bel* (x_t), over the state space conditioned on the information contained in the sensor data. The update of Bayes filter is performed in two steps (FOX et al 2003):

Prediction:

At each time update, the state is predicted according to the following update rule.

$$Bel^{-}(x_t) \leftarrow \int p(x_t \mid x_{t-1})\, Bel(x_{t-1})\, dx_{t-1} \tag{3.8}$$

Here, $p(x_t \mid x_{t-1})$ shows how system’s state changes over time.

Correction:

Whenever new information z_t is received, the measurement is used to correct the predicted belief using the observation.

$$Bel(x_t) \leftarrow \alpha_t\, p(z_t \mid x_t)\, Bel^{-}(x_t) \tag{3.9}$$

Where, $p(z_t \mid x_t)$ describes the possibility of making observation z_t given that the given the person is at location x_t and α_t is a normalizing constant which ensures that the posterior over the entire state space sums up to one.

Bayes filters are an abstract concept in that they provide only a probabilistic framework for recursive state estimation.

FOX et al (2003) have mentioned different implementations of Bayes filters which differ in the representation of probability densities over the state x_t.

Kalman filter

Kalman filters are the most widely used implementation of Bayes filters. These filters characterize the probabilities by uni-modal Gaussian distribution to compute only the mean and the covariance statistics. To compute the best estimate of the state and its uncertinity, update the previous estimates with the new measurements. Therefore, no need to consider all the previous data again. The main advantage of Kalman filters is their computational efficiency.

Multi-hypothesis tracking (MHT)

MHT has the ability to represent multi-modal belief using Kalman filter. It can overcome the limitations of Kalman filter to uni-modal distribution. Due to this property of MHT, it is more widely applicable than Kalman filter at the cost of intensive computations and requires sophisticated techniques to determine when to add or delete hypothesis.

Grid–based approaches

It overcomes the restrictions imposed on Kalman filters by relying on discrete, piecewise constant representations of the belief. Merit of using grid-based approaches is that they can represent arbitrary distributions over the discrete state space. It is more applicable to low dimensional estimation problems due to its computational and space complexity.

Topological approaches

Non-metric representations of an environment can avoid the computational complexity of grid-based approaches. For instance, graph structures are well suited to represent the motion of people in buildings or in cities. Such representations results in topological implementations of Bayes filters. Advantage of these approaches is their efficiency, because they represent distributions over small, discrete state space and their disadvantage is the coarse representation.

Particle filters

Particles filters represent beliefs by set of weighted samples distributed according to the belief. Practical filters key point is their ability to represent arbitrary probability densities. It is not suitable for high dimensional estimations as their complexity increases exponentially in the dimensions of state space.

Table 2. Comparing Bayes filter implementations.

	Kalman	**Multi-hypothesis tracking**	**Grid**	**Topology**	**Particle**
Belief	Uni-modal	Multi-modal	Discrete	Discrete	Discrete
Accuracy	Good	Good	Neutral	weak	Good
Robustness	Neutral	Good	Good	Good	Good
Sensor variety	Weak	Weak	Good	Neutral	Good
Efficiency	Good	Neutral	Weak	Neutral	Neutral
Implementation	Neutral	Weak	Neutral	Neutral	Good

Table 2 summarizes the advantages and disadvantages of different Bayes filter implementations (Fox et al 2003). Kalman filters and MHT require accurate sensors with rather high update rates. Topological approaches require sensors that relate to an environment's layout. Grid-based approaches and particle filters can incorporate virtually any sensor type. Kalman filters are the most efficient in terms of memory and computation. Grid-based approaches can reach arbitrary accuracy but at prohibitively high computational costs. Kalman filter's limited robustness is due to the uni-modal belief representation. Topological approaches provide a good way to estimate a person's location, if accurate location estimates are not required. Particle filters are an extremely flexible tool with low implementation overhead.

3.2.4 Radio path effects

Miniaturization of sensor nodes is very important in wireless sensor network, which results in use of low power radio transceiver to reduce energy consumption. Due to this constraint, the radio signal strength may be weak and the radio channels may be unreliable (Scott, Wu & Hoffman 2006). Irregularity of propagation patterns is essential reason for asymmetric radio interference and asymmetric links in upper layers. Average distance between nodes can vary the percentage of asymmetric links in a system (Zhou, He, Krishnamurthy, Stankovic 2004).

Radio irregularity is very common and non-negligible issue in wireless communication. Different packet losses in different directions and irregularity in radio range are caused by radio irregularity. Irregularity of spherical radio range degrades the performance of localization protocols like, Distance Vector (DV)-Hop and Centroid. Thus, in the presence of radio irregularity, assurance of full coverage may not be possible by sensing coverage scheme and blind points would occur. Radio irregularity has a significant impact on location based routing protocols as well, such as Geographic Forwarding (GF), than on–demand protocols , such as AODV and DSR, that use multi-round discovery technique (Zhou et al 2004).

In the Degree of Irregularity (DOI) model, DOI is used to denote the irregularity of radio pattern. The DOI model only models an absolute range based on the distance and determines whether one node can hear another node only by comparing the distance between these nodes with the sender’s communication range. Communication range becomes more and more irregular by increasing the DOI value (Zhou et al 2004).

Path loss

In wireless sensor networks, radio irregularity is mainly caused by the variance in the signal path loss, i.e., non-isotropic path loss. When a signal travels within a medium, it may be reflected, scattered and diffracted. The radio signal from a transmitter has different path loss in different directions is termed as non-isotropic path loss (Scott 2006). Non-isotropic path loss may also be due to the non-isotropic antenna gain of each node. Path loss describes the energy loss of a signal as it travels to the receiver. Generally path loss is referred as long term fading. Free space propagation model, the two-ray model and the Hata model, all these models are used to estimate isotropic path loss, i.e., the path losses in different directions are the same (Zhou 2004). Narrow band measurements are used to compute the path loss of channel, in time domain. Path loss (or spreading loss) is not frequency dependent in free space (LOS environment) (Darbari, Mcgregor, Whyte, Stewart & Thayne 2005). Less path loss can be possible by using low frequencies which give better range than high frequencies which result in smaller sensor nodes. Characterization and modeling of the propagation path loss is needed for the design and deployment of a robust sensor system.

Asymmetric antenna pattern

In sensor system, the interface between the RF channel and the system's hardware is provided by the antenna. It is one of the key components in sensor system and one of the main causes of radio irregularity. High efficiency antennas are required for successful communication between nodes as antenna size is a design constraint. Large sized antenna is capable of using low frequencies, where as, for high frequencies small size antenna is used (MICROWAVES & RF 2005). Antennas for sensor systems can be directional or omni-directional, based on the requirement of the system. Directional antennas are used to reduce the chance of receiving undesired signals from the surrounding environment and to extend the communication range of the system with limited coverage. Omni-directional antennas receive or radiate equally in all directions and have shorter range. It is also called non-directional antenna because it does not favor any particular direction. Omni-directional antennas are useful for broadcasting a signal to all points of the compass or when listening for signals from all points (Carr).

Radiation pattern of an antenna may vary from one node to another within the system. This difference in radiation patterns might be possible due to many factors. Conducting materials create the most destructive interface, if they are placed very close to the antenna (DarbarI et al 2005). The antenna is enclosed in the node; the surrounding objects that may cover the node could distort the patterns. Radiation patterns can also be distorted from non conducting objects. Those objects with dimensions near the length of the antenna behave as parasitic elements of an uncontrolled array, producing random null in the antenna radiation pattern (MICROWAVES & RF 2005). Radiation pattern is also dependent on the type of antenna used (Scott et al 2006).

Radiation pattern for directional antenna is more focused in the LOS than non directional, that's why; the gain of directional antenna is greater than non directional as directivity is directly proportional to the gain. The non-isotropic antenna gain of each node also contributes to the non isotropic path loss (Zhou et al 2004). This asymmetric antenna radiation pattern may generate uni-directional links between sensor nodes. Such problems can not be addressed without introducing large control overhead. The coverage area will be affected by the asymmetric antenna radiation pattern. Therefore, hardware designers should consider these problems.

Multi-path

Multi-path fading heavily contributes to the unreliability of wireless links in wireless sensor networks. A transmitted radio signal that is reflected from obstacles and reaches to the destination by taking two or more paths is referred as multi-path. Signal attenuation and distortion due to multi path propagation is termed as multi-path fading or multi-path interference. Those signals which take the most direct path are considered strongest and less attenuated as compared to the signals which travel least direct route; they are highly distorted and attenuated so they are considered very weak. Multi-path fading only depends on the topology of the environment where nodes are deployed (Puccinelli & Haenggi 2006). Rayleigh distribution is commonly used to model the multi-path fading in wireless sensor network (Zhou et al 2004). Fading level can be deterministically computed if the position of the terminals and geometry of the environment, where network is deployed, are known at all times. Higher values of omni-directional antenna are used to receive more multipath.

In wireless sensor network, packet loss is also common due to the poor radio channel conditions. Proper mechanisms and accurate models are required to deal with the problem of radio irregularity which has a direct impact on the upper layer protocols, such as localization, routing and tracking.

CHAPTER 4

MULTI-DIMENSIONAL SCALING

Multidimensional scaling (MDS) is a data analysis technique to compute relative positions of adjacent sensors from high dimension space to low dimension space with high error-tolerance (Ji & Zha 2004; Shang, Ruml, Zhang & Fromherz 2003). MDS requires only connectivity information to produce a meaningful result. The main idea in performing MDS is to make data more understandable by representing data graphically.

MDS was originally developed for use in psychophysics and psychometrics, it comes in variety of related geometric models like, similarity judgments, marketing, sociology, physics, biology, political science and presently it is mostly used as a data exploration technique or information visualization (Tulabandula 2007; Shang et al 2003; Bachrach & Taylor 2008). MDS works well in sensor localization domain as well. It uses the distance information between nodes to determine the coordinates of nodes in a 2D or 3D space. MDS is related to principal component analysis, factor analysis and cluster analysis.

MDS is a centralized approach which can be used for both relative and absolute position estimation of nodes. MDS can always generate high accurate position estimation even based on limited and error-prone distance information. MDS yields coordinates that provides the best fit to the estimated pairwise distances, but which lie at an arbitrary rotation and translation because the inter-point distances make no reference to any absolute coordinates. If anchor nodes (known coordinates of nodes) are available, they can be used to derive the linear transformation of the MDS coordinates that allows the best match to the known positions (Tulabandula 2007; Shang et al 2003).

MDS is a generic term that includes many different specific types. This classification is based on either geometry or dimension used to map the data, or the number of similarity metrics used in the scaling, or the mapping function, or the statistical error or the stress function being optimized. They can also be classified as the similarity data is metric (quantitative) or non metric (qualitative). Classical MDS uses one matrix. Replicated MDS uses several matrices, representing distances measurements taken from several subjects or under different conditions. Weighted MDS uses a distance model which assigns a different weight to each dimension. Finally, there is a difference between deterministic and probabilistic MDS. In deterministic MDS, each object is represented as a single point in a multidimensional space, whereas in probabilistic MDS each object is represented as a probability distribution over the entire space (Tulabandula 2007; Shang et al 2003).

Classical MDS is the simplest type of MDS. It uses only one matrix of dissimilarity or similarity as distance information because the dissimilarity information is quantitative and computes the coordinates that explain the dissimilarity matrix. Classical MDS yields relative location estimation of the nodes and if 3 or 4 anchors in 2-dimension and 3-dimension respectively, are available then the transformation of relative map to absolute map is possible (Tulabandula 2007). Classical metric MDS is robust in tolerating measurement errors of sensor distance because it has analytical solutions.

4.1 Solving the coordinates by using MDS

MDS is a localization method based on distance matrix singular value decomposition (SVD) (Shang et al 2003). In general SVD of matrix A is defined as:

$$A = U\,S\,V^T \qquad (4.1)$$

Where *S* is a diagonal matrix having the singular values of *A* in it's diagonal in decreasing order. *U* and *V* are unitary matrices. The first *r* columns of the orthogonal matrices *U* and *V* define the orthogonal eigenvectors associated with *r* nonzero eigenvalues of *AAT*.

Assume that we have a set of nodes in the Euclidean space and we can measure all pairvise distances between the nodes. In that case we have

$$I\,(P) = D + E \qquad (4.2)$$

Where *I (P)* is a linear transformation of the proximities, *E* is a matrix of errors and *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.

Any point can be selected to be the origin, but a double-centering is recommended, because setting the origin to the center of the space tends to minimize the random errors in the distance measurements.

If *D* is the *n* x *n* distance matrix, it is converted to double-centered distance matrix *B* by conversion

$$B = -\frac{1}{2}\left(I - \frac{1}{n}U\right) D^2 \left(I - \frac{1}{n}U\right), \qquad (4.3)$$

Where *U* is an *n* x *n* matrix consisting entirely of ones, *I* is an *n* x *n* identity matrix and *D*’s exponent 2 indicates that all elements of matrix *D* are squared.

In this type of relative map definition, B is a symmetric square matrix which means that

$$B = B^T \qquad (4.4)$$

It is shown in linear algebra that the decomposition of a quadratic matrix into the product LHU, where L is lower triangular, U is upper triangular and H is diagonal matrix, is unique. Thus,

$$B = LHU = B^T = (LHU)^T = U^T H^T L^T \qquad (4.5)$$

So,

$$L = U^T \ , U = L^T \text{ and } H = H^T \qquad (4.6)$$

As a consequence, for symmetric matrix B,

$$B = LHU = LHL^T, U = L^T \tag{4.7}$$

By splitting *H* into two matrices we get

$$B = LHL^T = LH^{\frac{1}{2}} H^{\frac{1}{2}} L^T = \left(LH^{\frac{1}{2}}\right) \left(LH^{\frac{1}{2}}\right)^T = XX^T \tag{4.8}$$

The solution of coordinate matrix *X* becomes

$$X = LH^{\frac{1}{2}} \tag{4.9}$$

The factorization of *B* presented above is called orthogonal diagonalization and it is always possible for square symmetric matrices. The ortogonalization of a square symmetric matrix *B* is a special case of SVD. Thus, we can compute the SVD of *B*

$$B = USV^T = USU^T = XX^T \tag{4.10}$$

And solve the coordinate matrix *X*

$$X = US^{\frac{1}{2}} \tag{4.11}$$

MDS-MAP

MDS-MAP is a centralized algorithm based on multidimensional scaling (MDS). It is almost a direct application of the simplest type of MDS: classical metric MDS. It determines the positions of nodes with basic connectivity or distance information like which nodes are within communications range of which others. MDS-MAP estimates improve as ranging improves. It is able to generate both relative and absolute maps of the network. Moreover, there are no rules where to place the anchor nodes within the network. This is very helpful in applications of sensor networks deployed in harsh environment to position anchor nodes is difficult to reach positions. This algorithm is also helpful in applications like location aided routing and also low budget applications that can not afford highly sophisticate devices for anchors.

MDS-MAP consists of 3 steps:

1. The distance matrix is calculated in this step using either Dijkstra's or Floyed's all pairs shortest path algorithm. This distance matrix serves as input to the MDS in step 2.
2. Classical MDS is applied to the distance matrix which gives relative map of the true node positions.
3. In this step, relative map is transformed into absolute map with sufficient number of anchor nodes.

MDS- MAP uses the distance or connectivity information between all nodes at the same time, whereas triangulation-based methods localize one unknown node at a time and only use the information between the unlocalized and anchor nodes (Tulabandula 2007).

4.2 Centralized implementation

Several localization methods have been developed, based on classical MDS are called MDS-MAP methods. MDS-MAP(C) is the simplest method of MDS-MAP that builds a global map using classical MDS, where the parameter C is for classical. In this method, computation of connectivity information of the network is done at central location (Shang et al 2003).

There are three steps of MDS-MAP(C):

1. Compute shortest paths between all pairs of node in the region of consideration.
2. Apply classical MDS to the distance matrix to drive node localizations that fit those distances.
3. Transform the relative map to an absolute map with the help of anchors.

In step 1, starting with the given local distance measurements of network, assign distances to the edges in the connectivity graph. When the distance of a pair node is known, the value of the corresponding edge is the measured distance. Then, Dijkstra's or Floyd's algorithm, all-pairs shortest path algorithm can be applied. The shortest path distances are used to construct the distance matrix for MDS.

In step 2, classical MDS is applied to the distance matrix. Hold the first 2 (or 3) largest eigenvalues and eigenvectors to construct a 2-D or 3-D relative map. The result of MDS is an arbitrarily rotated and flipped relative map that gives a location for each node.

In step 3, transform the relative map to an absolute map through linear transformation, which includes scaling, rotation and reflection. The basic idea behind this is to minimize the sum of squares of the errors between the transformed positions of anchors in the MDS map and the true positions of the anchors.

When the accurate distance measures between one-hop neighbors are known, the result of MDS-MAP(C) can be improved by adding refinement to MDS-MAP(C), this is called MDS-MAP(C,R). The parameter R refers to refinement. In MDS-MAP(C,R), a refinement step is added between steps 2 and 3 of MDS-MAP(C) to improve the solution computed by MDS. In the refinement, least squares minimization is used to make the distances between neighboring nodes match the provided measured ones.

MDS-MAP(C) and its variant MDS-MAP(C,R) do not give good results in anisotropic topologies as compared to the isotropic topologies because the short path distance between nodes in the two wings is much bigger than their actual Euclidean distance (Shang et al 2003). Patched MDS-MAP methods are developed to address this problem.

4.3 Distributed implementation

In classical MDS, distance between every pair of nodes is required. The shortest path distance between two nodes provides an estimate of the true Euclidean distance. This estimate gives good result in dense or in uniform network but does not fit fine in very irregular networks. When the estimation is off, the result of classical MDS is also badly affected. The new methods, MDS-MAP(P) and MDS-MAP(P,R), based on MDS-MAP are developed that work well in both uniform and irregular networks (Shang & Ruml 2004; Shang et al 2003).

MDS-MAP(P) is more complicated than MDS-MAP(C), the parameter P refers to patch. It builds patches of local maps and then merges them to form a global map. In MDS-MAP(P), each node simultaneously computes its own local map (includes only relatively nearby nodes) using MDS-MAP. Two maps are then merged together based on their common nodes to form a global map. This method depends on local information and avoids using the distance estimation between remote nodes. Thus, the local maps have to be accurate enough so that when they are merged together to form a global map, errors will not become too large.

The steps of MDS-MAP(P) are as follows (Shang & Ruml 2004; Shang et al 2003):

1. Set the range for local maps, R_{lm}. For each node, neighbors within R_{lm} hops are involved in building its local map.
2. Compute local maps for individual nodes. For each node, do the following:
    a. Compute shortest paths between all pairs of nodes in its local mapping range R_{lm}. The shortest path distances are used to construct the distance matrix for MDS.
    b. Apply MDS to the distance matrix and retain the first 2 (or 3) largest eigenvalues and eigenvectors to construct a 2-D (or 3-D) local map.
    c. Refine the local map. Using the node coordinates in the MDS solution as the initial point, perform least squares minimization to make the distances between nearby nodes match the measured ones.
3. Merge local maps. Local maps can be merged sequentially or in parallel. There are various ways of merging local maps sequentially, such as randomly or according to certain order best for an application.

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

To improve the global map, a refinement is added to MDS-MAP(P). The method is called as MDS-MAP(P,R), where R is for refinement. In MDS-MAP(P,R), a refinement step using least square minimization is added between step 3 and 4 of MDS-MAP(P) to improve the global relative map. The refinement technique improves the relative maps by forcing them to conform more closely to the distances to nearby neighbors. The cost of refining the global map grows quickly and becomes dominant for large networks.

MDS-MAP(P) can be done in a distributed fashion, which makes it appropriate for large-scale networks. In a distributed implementation of MDS-MAP(P), the computational cost is proportional to the size of the local maps.

In uniform networks, MDS-MAP(P) and MDS-MAP(P,R) gives consistently much better results than DV-hop and DV distance, whereas in C-shaped networks MDS-MAP(P) and MDS-MAP(P,R) are not better than DV-hop and DV distance when connectivity is low (Shang & Ruml 2004; Shang et al 2003).

Comparing the classical MDS and patched MDS methods, the MDS-MAP(C) suffers from long-range distance estimation errors and MDS-MAP(P) suffers from error propagation.

CHAPTER 5

SIMULATIONS AND RESULTS

As main focus of this master's thesis is to compare the distance-based wireless sensor node localization techniques, RSSI, Ultrasound and UWB; comparisons are done on the virtual WSN and computations are performed in Matlab. Sensorviz is used to simulate virtual WSN.

Sensorviz is a wireless network simulation and visualization tool written by Andreas Savvides. The Sensorviz java utility was modified such that it will now output the beacon nodes, their positions, radio ranges, sensor ranges, edges and all of the edge distances. It can even connect to the real network.

5.1 Deployment of sensor node

The first step of the experiment is to simulate the network. Static sensor node is randomly deployed in the decided area of 100 m x 100 m two dimensional square with 50, 100 or 200 sensor nodes and radio range of each sensor node is 30m, 25m or 15m respectively and having the same sensor range according to the scene. It is assumed that each node has at least three one-hop neighbors. It is also assumed that each node is equipped with an ultrasonic transceiver or a radio module for ranging and communication, according to the scenario. Figure 6 is an example that shows 50 sensor nodes randomly deployed in an area of 100 x 100 and the blue circles show the ground-truth positions of the nodes.

There are three simulated network scenes which are used in the experiment. In first network scene, 50 sensor nodes with radio range of 30m in an area of 100 m x 100 m are simulated. In another network, sensor node is increased to 100 and radio range of each sensor node is decreased to 25m in the same area of 100 m x 100 m. In the final network scene, there are 200 randomly deployed sensor nodes in a decided area of 100 m x 100 m with 15m range of radio. All these three networks scenes are used every time in each distance-based localization techniques which are RSSI, ultrasound and UWB.

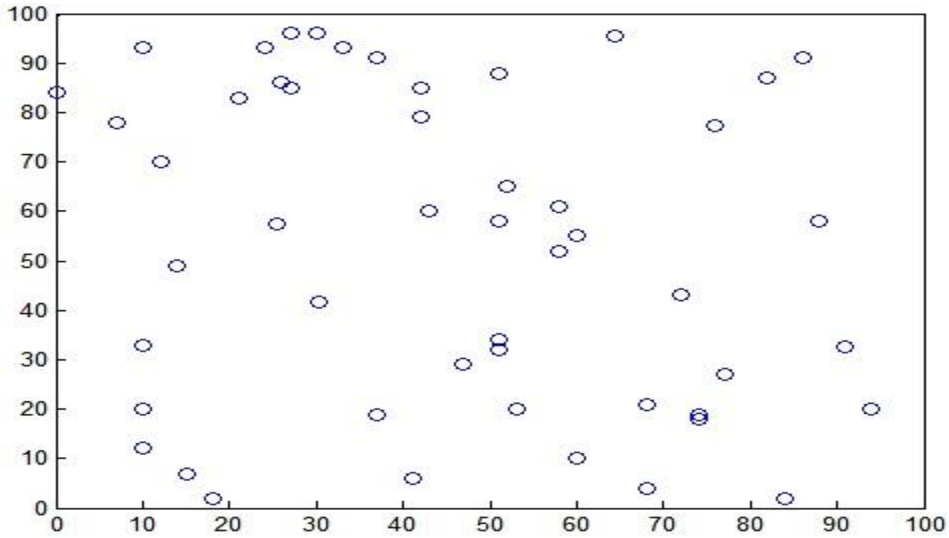


Figure 6. Ground-truth positions of 50 randomly deployed sensor nodes.

5.2 Sensor node localization

After the sensor nodes are deployed and network is simulated, a distance-based localization algorithm (RSSI, UWB or ultrasound) is executed to localize the nodes. In this thesis, MDS is applied for solving the coordinates. MDS is one kind of centralized localization method to solve a distance-based localization problem. Classical MDS is the simplest case of MDS. It provides the static sensor nodes to localize their positions by themselves. Classical MDS method can be separated into two main procedures: the MDS computation; and the coordinate transformation.

Computing relative localization

The first step of classical MDS is to calculate distance matrix either by using Dijkstra’s or Floyed’s all pairs shortest path algorithm. Floyed Warshall algorithm usually requires three inputs, which are number of nodes, connectivity matrix and distance matrix. Outputs of this algorithm, that are shortest paths with respect to number of hops, shortest paths with respect to Euclidean lengths and forwarding information for routing; serve as input in next MDS step.

After the shortest Euclidean path is computed by using the Floyd-Warshall algorithm, a new distance matrix with the measured distance is made. Classical MDS is applied to the distance matrix which gives relative map of the true node positions. Figure 7 shows the relative locations of the true node positions provided by MDS.

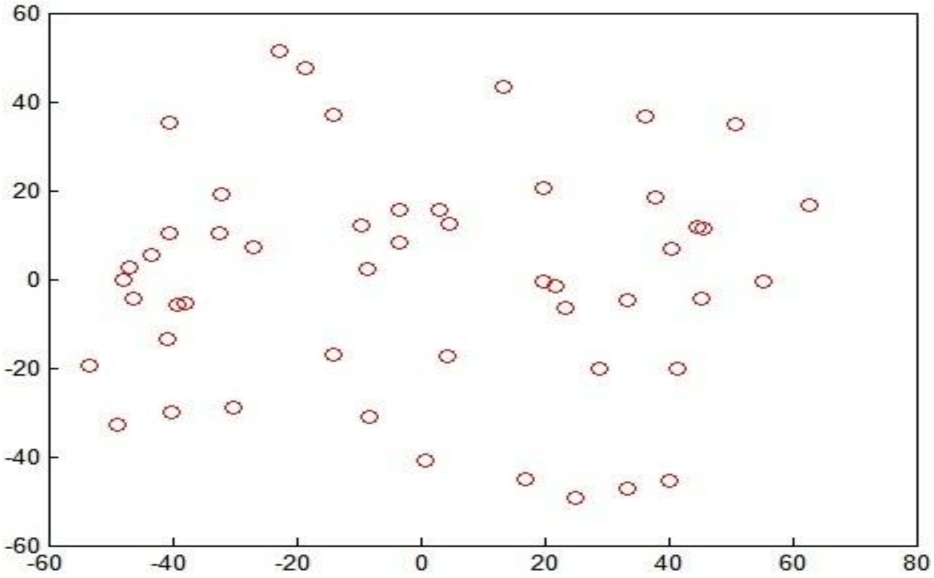


Figure 7. Relative locations of the true node positions.

Transformation to absolute map

In this step, relative map is transformed to an absolute map through linear transformation which includes scaling, rotation and reflection. For transforming the relative coordinates to the original absolute coordinates, three beacons are chosen to provide the transformation method. The reason behind this is to minimize the sum of squares of the errors between the transformed positions of anchors in the MDS map and the true positions of the anchors. Figure 8 shows the ground-truth locations compared with the transformed relative locations and the three nodes with blue star as the three beacons.

Once the positions of all sensor nodes are computed by using Classical MDS, the sensor nodes localize their location based on the new coordinates which appear as red stars in Figure 8.

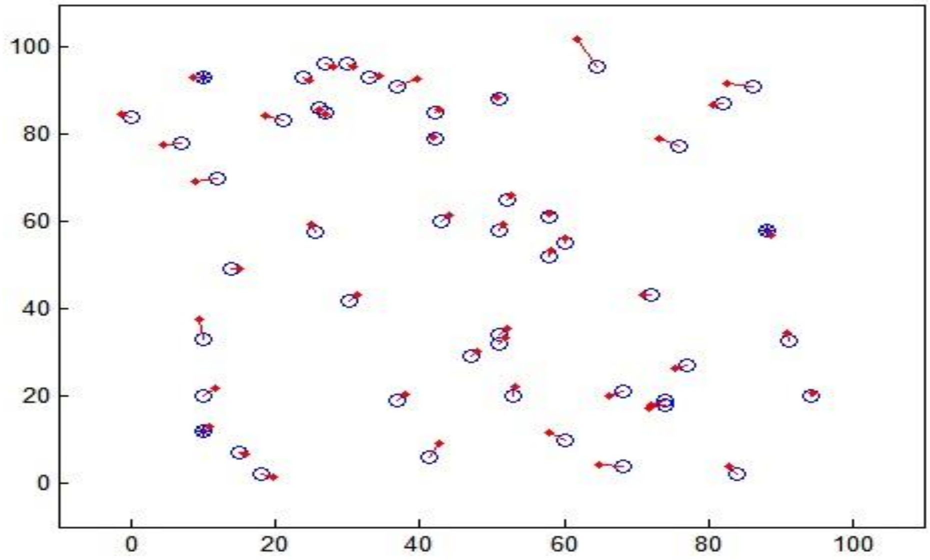


Figure 8. Ground-truth and transform relative locations.

5.3 Scenarios

After the simulation setup is ready, different data and parameters are obtained to provide the results analysis. Depending on different factors, the effect of the localization can be analyzed based on the collected data. The scenarios focus on analyzing the quality of distance-based sensor localization. Scenarios of the data collection are divided in to three directions; RSSI, ultrasound and UWB.

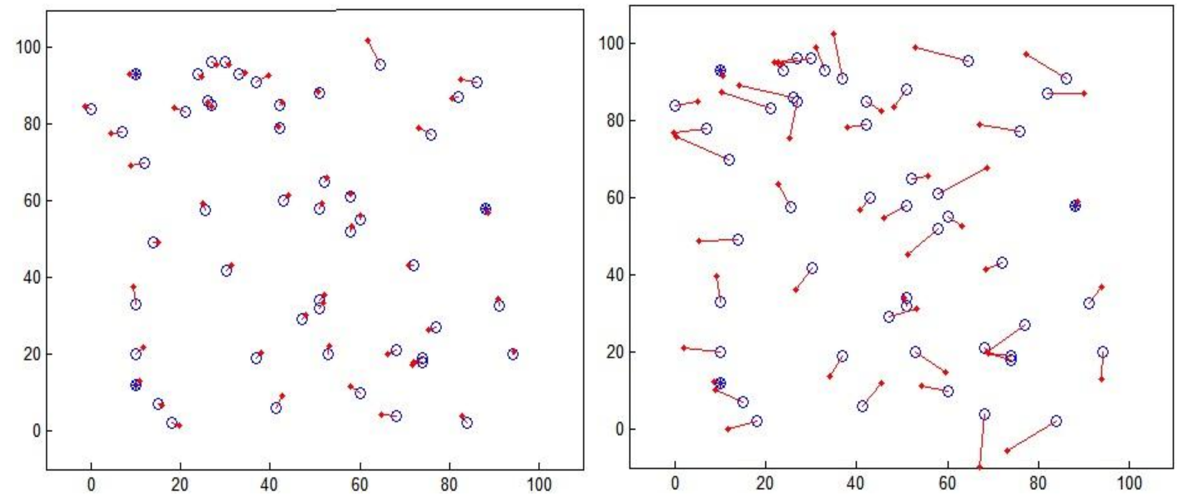
The testing are done on three different network scenes of randomly deployed static sensor nodes, all three network scenes are mentioned above. The effects of the Classical MDS method cause by the different range-noise levels are analyzed. It means, in every scene testing, the noise levels are 0%, 5%, 10% and 40%.

5.4 Results

After completing the testing scenarios in Section 5.3, the target data was recorded. As the results of the simulations, all the recordings were analyzed. It shows the performances of all simulations.

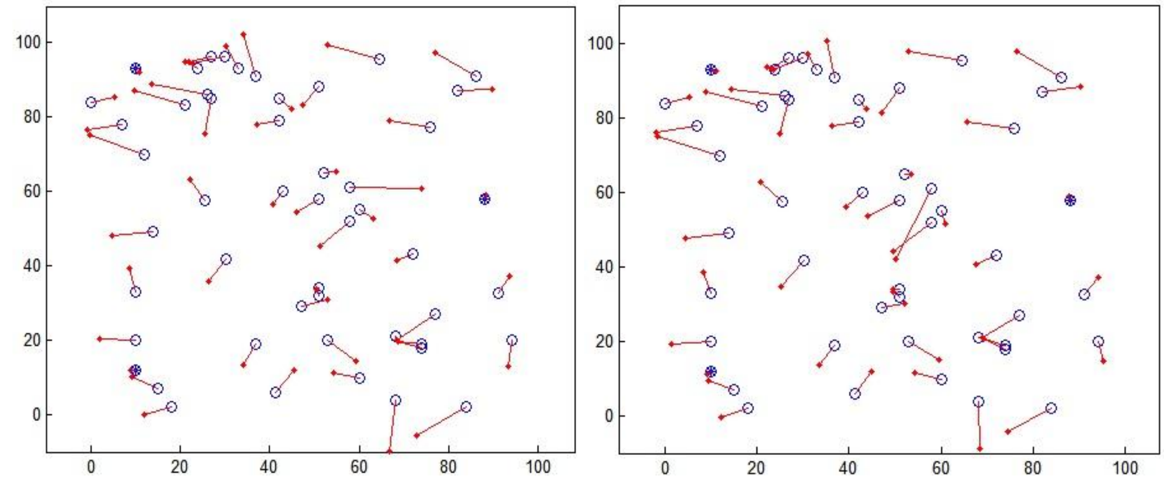
5.4.1 Noise in RSSI localization

Noise levels in RSSI localization are changed in three different scenes. Figure 9(a) is plotted when noise is 0% in scene1. RSSI gives very optimized result when there is no noise. By adding only 5% of range-noise, there is a considerable change in the resulting scene as shown in Figure 9(b). Figure 9(c) shows that by increasing the noise level from 5% to 10%, there is a very minimal change in the scene which is not noticeable. Even by increasing the noise to 40%, there are very small variations in the scene, shown in figure 9(d). These small variations are also verified by mathematical readings as shown in Table 3. Same scene1 is plotted in all variations of noise levels. This is done only to understand the behavior of RSSI in different range-noises.



(a) **(b)**

Figure 9(a). RSSI in scene1 with 0% noise; **(b).** RSSI in scene1 with 5% noise.



(c) **(d)**

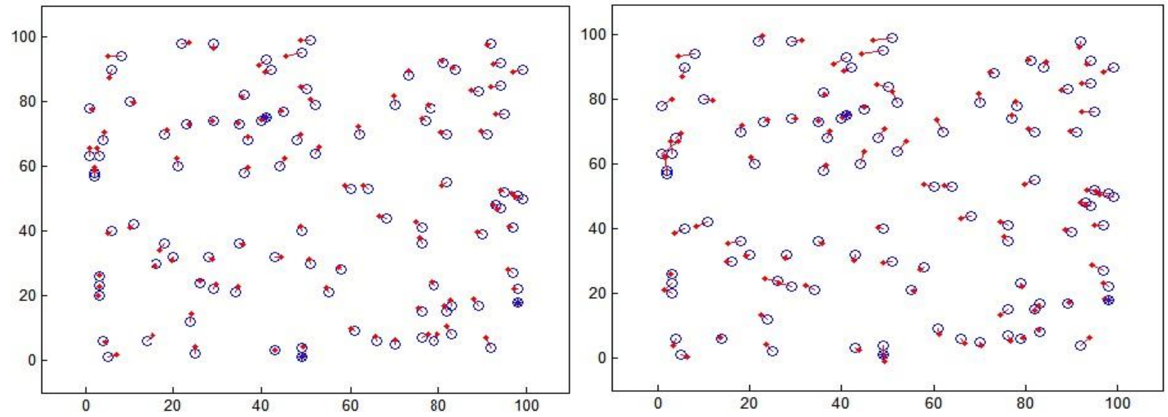
Figure 9(c). RSSI in scene1 with 10% noise; **(d)**. RSSI in scene1 with 40% noise.

Table 3. Outputs of RSSI in three different scenes with different noise levels (0%, 5%, 10% and 40%).

Scene 1				
Noise (%)	0	5	10	40
Distance_error_squaresum	1.0816e+004	3.0074e+006	3.0071e+006	3.0081e+006
Average_distance_error	2.3446	44.6275	44.6206	44.6368
Relative_to_range	0.0782	1.4876	1.4874	1.4879
Scene 2				
Noise (%)	0	5	10	40
Distance_error_squaresum	3.1176e+004	1.3082e+007	1.3082e+007	1.3082e+007
Average_distance_error	2.0806	46.6120	46.6121	46.6127
Relative_to_range	0.0832	1.8645	1.8645	1.8645
Scene 3				
Noise (%)	0	5	10	40
Distance_error_squaresum	7.8565e+005	3.6416e+007	3.6414e+007	3.6447e+007
Average_distance_error	5.0514	38.6793	38.6779	38.6973
Relative_to_range	0.3368	2.5786	2.5785	2.5798

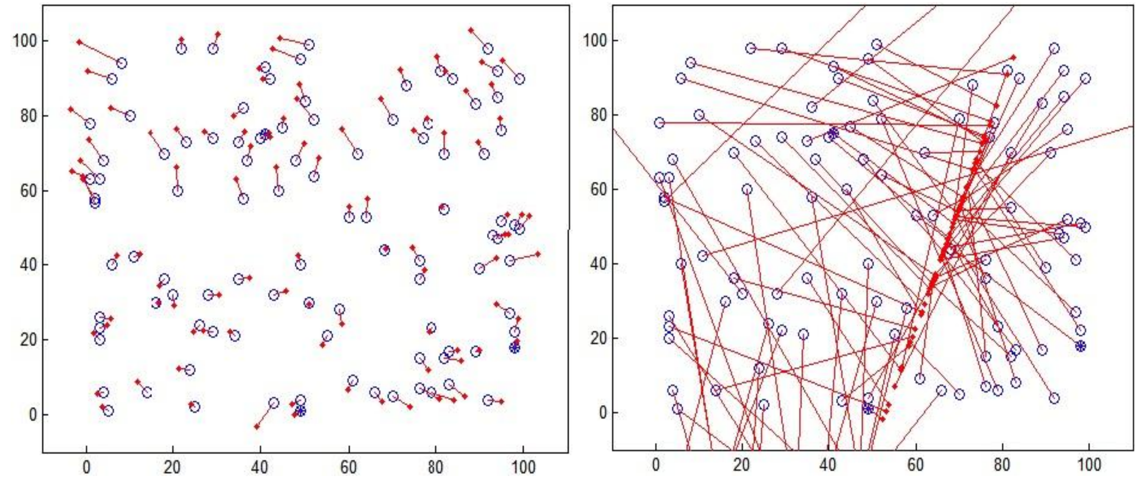
5.4.2 Noise in ultrasound localization

Behavior of ultrasound in different scenes is observed by changing the range-noise levels. Scene2 is used in all figures of ultrasound localization. Figure 10(a) shows the behavior of ultrasound when there is no noise (0% noise) in the scene. In the resulting scene, ground truth and estimated positions provided by MDS, have almost the same positions, when radio range is 25m. In the Figure 10(b), there is very small difference between ground truth and estimated position with 5% noise. Figure 10(c) depicts that the difference between the positions is increased as the noise level is increased from 5% to 10% but still the difference is not much. In Figure 10(d), there is a very large difference between the ground truth and estimated positions of ultrasound. The analyzed data shows an increase in average-distance error as the range-noise is increased.



(a) **(b)**

Figure 10(a). Ultrasound with 0% noise; (b). Ultrasound with 5% noise.



(c) **(d)**

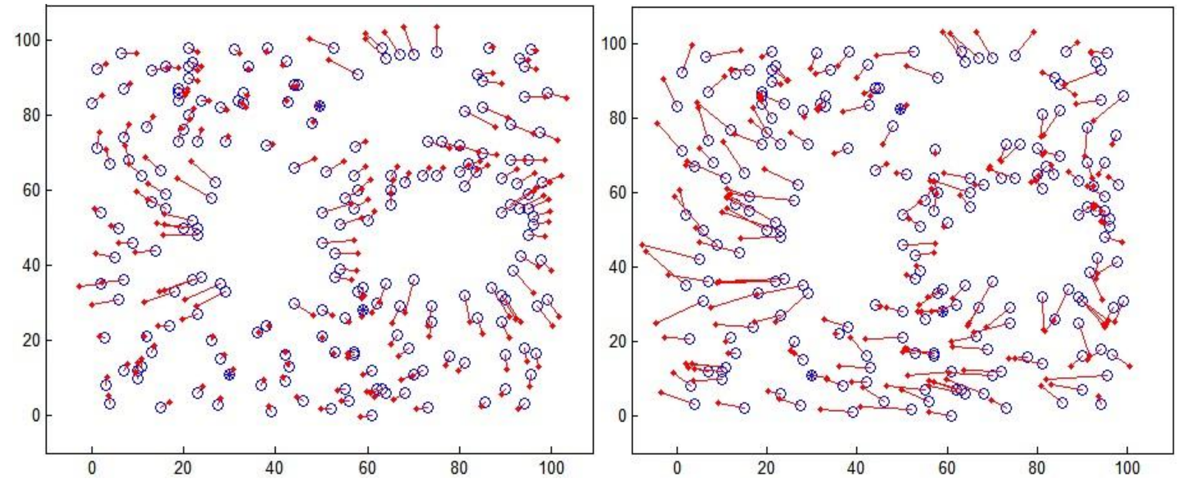
Figure 10(c). Ultrasound with 10% noise; (d). Ultrasound with 40% noise.

Table 4. Outputs of ultrasound in three different scenes with different noise levels (0%, 5%, 10% and 40%).

Scene 1				
Noise (%)	0	5	10	40
Distance_error_squaresum	1.0816e+004	8.5776e+003	2.0442e+004	1.6997e+006
Average_distance_error	2.3446	2.0906	3.3506	32.5469
Relative_to_range	0.0782	0.0697	0.1117	1.0849
Scene 2				
Noise (%)	0	5	10	40
Distance_error_squaresum	3.1176e+004	3.5415e+004	1.2232e+005	6.7380e+009
Average_distance_error	2.0806	2.1426	4.0822	306.6466
Relative_to_range	0.0832	0.0857	0.1633	12.2659
Scene 3				
Noise (%)	0	5	10	40
Distance_error_squaresum	7.8565e+005	5.8247e+005	5.1075e+005	4.0401e+015
Average_distance_error	5.0514	4.1761	3.9971	9.0677e+004
Relative_to_range	0.3368	0.2784	0.2665	6.0451e+003

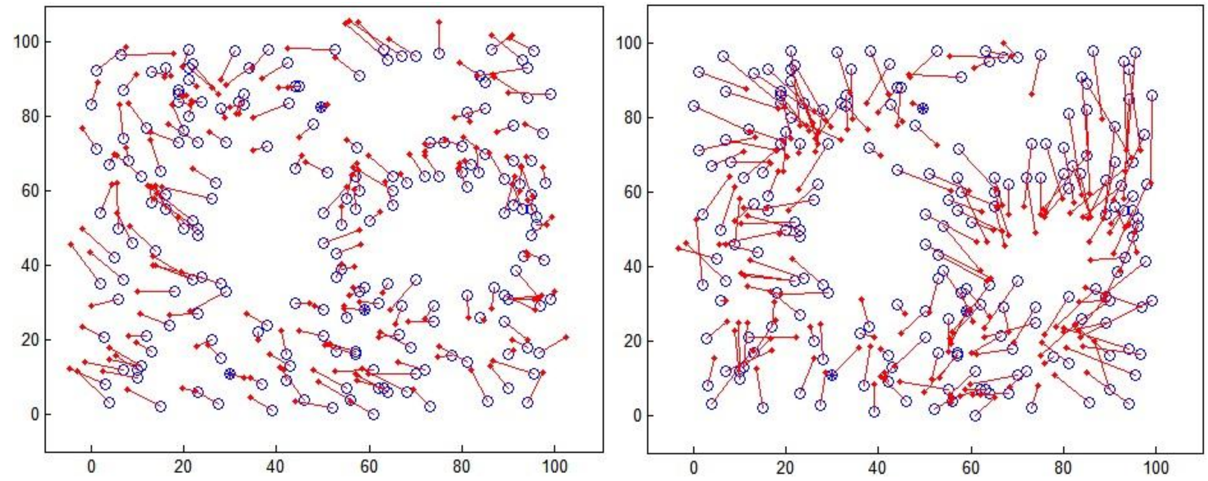
5.4.3 Noise in UWB localization

Noise levels in UWB localization are changed in three different scenes. Scene 3 is used in all figures of UWB localization. Figure 11(a) shows UWB in a large network of 200 sensor nodes with no noise. There are small differences between the ground truth and estimated positions of UWB when noise is added by 5%, as shown in Figure 11(b). Figure 11(c) depicts the increase of noise level from 5% to 10 %. Variations in distances are very small as noise is increased by 5%. Figure 11(d) shows UWB with 40% noise. Small variations in distances are gradually increased as noise levels are increased.



(a) **(b)**

Figure 11(a). UWB with 0% noise in scene 3; (b). UWB with 5% noise.



(c) **(d)**

Figure 11(c). UWB with 10% noise; (d). UWB with 40% noise.

Table 5. Outputs of UWB in three different scenes with different noise levels (0%, 5%, 10% and 40%).

Scene 1				
Noise (%)	0	5	10	40
Distance_error_squaresum	1.0816e+004	1.6400e+018	1.1985e+018	6.1039e+017
Average_distance_error	2.3446	3.2928e+007	2.8007e+007	1.9604e+007
Relative_to_range	0.0782	1.0976e+006	9.3357e+005	6.5346e+005
Scene 2				
Noise (%)	0	5	10	40
Distance_error_squaresum	3.1176e+004	1.0408e+019	8.6275e+018	3.2832e+018
Average_distance_error	2.0806	4.1584e+007	3.7857e+007	2.3126e+007
Relative_to_range	0.0832	1.6634e+006	1.5143e+006	9.2503e+005
Scene 3				
Noise (%)	0	5	10	40
Distance_error_squaresum	7.8565e+005	1.2808e+020	1.1225e+020	5.3127e+019
Average_distance_error	5.0514	7.2605e+007	6.7963e+007	4.6622e+007
Relative_to_range	0.3368	4.8403e+006	4.5309e+006	3.1082e+006

CHAPTER 6

CONCLUSION

Wireless sensor networks are a significant technology attracting considerable research interest. Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power and multi-functional sensors that are small in size and communicate in short distances. Location awareness is important for wireless sensor networks since many different critical applications such as inventory management, intrusion detection, road traffic monitoring, health monitoring, environmental monitoring and surveillance depend on knowing the locations of sensor nodes.

Considering hardware capabilities, available localization methods can be distinguished into two classes: distance-based and connectivity-based. Distance-based techniques use inter-sensor distance or angle measurements in location calculation. Distance-based algorithms give good estimation of location though it requires additional equipment. Whereas, connectivity-based algorithms use only the contents of the received messages to locate the entire sensor network.

In this thesis, MDS, a simple approach for solving the localization problem in WSN is used. This mathematical approach is able to derive the locations of nodes with accuracy equal to 20% of range of each node. MDS-MAP is able to derive both the relative and absolute maps of the network.

As the target of this master’s thesis, research is focused on which distance-based sensor node localization techniques give good quality of measurement in terms of accuracy. By using the Sensorviz simulation tool, different scenarios are simulated and obtained results are analyzed.

According to the results of RSSI localization in three different scenarios, it is analyzed from the obtained data that RSSI gives optimized result when there is no noise. If there is noise in the network, either small percentage of noise or large percentage of noise, the effect of noise variations in measurement is not much. RSSI is attenuated by large-scale path losses, frequency selective fading and shadowing losses.

Results of ultrasound localization show that ultrasound performs well in calm conditions. It is not feasible in noisy environment. If there is small percentage of noise, it gives relatively better result than in the presence of large percentage of noise. RSSI performs comparatively better than ultrasound if the environment is very noisy. The accuracy of ultrasound is high in short distances. Environmental conditions (temperature, relative humidity and atmospheric pressure) and sound reverberating effects affect the ultrasound's accuracy.

The range-based time of arrival (TOA) approach is the most suitable approach for localization in UWB sensor networks, because it is proved to have a good accuracy due to the high time resolution (large bandwidth) of UWB signals. UWB localization technique offers a good performance in noisy environment. The ranging accuracy depends on the accuracy of calculated two way time of arrival. The main sources of ranging errors in UWB ranging systems are multipath propagation, NLOS propagation and multi-user interference (MUI).

Each distance based technique has its strong and weak points and can be used according to the conditions and requirements.

Bayesian filter techniques provide a powerful tool which deals with uncertainty of measurements. Bayes filters probabilistically estimate a dynamic system's state from noisy observations.

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