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With title of

**Evaluation of error estimation in DV-
Hop for Wireless Sensor Networks**

تقييم دقة تقدير الخطأ لعملية منهجة المسافة لشبكات الحساس اللاسلكية

Prepared By:

Muhammed Osama Abdou Merghani

Supervisor:

Dr. Ashraf Gasm Elsid Abdullah

January 2016



Sudan University of Science and Technology
College of Graduate Studies



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Candidate's name: *Muhammed Osama Abdou Merghani*

Candidate's signature: *[Signature]* Date: *[20/3/2016]*

إقرار

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*تصميم دقة الخطأ العملية من وجهة المساحة لشبكات الحساسات
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اسم الدارس: *محمد Osama عبد مرغاني*

توقيع الدارس: *[Signature]* التاريخ: *20 مارس 2016*



Approval Page

Name of Candidate: Muhammed Osama Abdou

Thesis title: Evaluation of error estimation
D.V. λ for WSN

Approved by:

1. External Examiner

Name: Dr. Osman Mudathir Elfdil

Signature: [Signature] Date: 20/1/2016

2. Internal Examiner

Name: Dr. Rashid A. Saeed

Signature: [Signature] Date: 20/1/2016

3. Supervisor

Name: Dr. Ashraf Gasim Elsid Abdalla

Signature: [Signature] Date: 20/1/2016



قَالَ الَّذِي عِنْدَهُ عِلْمٌ مِّنَ الْكِتَابِ أَنَا آتِيكَ بِهِ قَبْلَ أَن يَرْتَدَّ
إِلَيْكَ طَرْفُكَ ۚ فَلَمَّا رآه مُسْتَقِرًّا عِنْدَهُ قَالَ هَٰذَا مِن
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صدق الله العظيم

سورة النمل - آية 40

Dedication

*This work is dedicated to my family
Who were always there supporting me
And also dedicated to the one who has lift our
life after a long period of donation in high
education field
Prof. Elsiddiq Hassan Alsafi...*

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Abstract

The *Wireless Sensor Networks (WSNs)* consist of spatially distributed wireless sensor nodes that cooperate with each other in order to monitor and collect data pertaining to physical or environmental conditions such as temperature, pressure, motion, sound, and other phenomena. The locations of the sensor nodes are not predetermined as they are usually randomly deployed in the region of interest. Therefore, *Localization* algorithms that can compute the location of sensor nodes within a *WSN* are needed.

There are mainly two types of *localization* algorithms. The Range-based *localization* algorithm has strict requirements on hardware, thus is expensive to be implemented in practice. The Range-free *localization* algorithm reduces the hardware cost. However, it can only achieve high accuracy in ideal scenarios. *Distance Vector Hop (DV-Hop)* is the mostly range-free algorithm used.

In this thesis, i review and estimate the *DV-Hop* performance limit by changing positioning method. The most unsighted parameter is mean absolute error which has been demonstrated in the Simulation results.

Simulation results show that the localization mean absolute error for both multilateration and bounding box methods are different. However, the *localization* accuracy in bounding box is far smaller than that of the multilateration. Therefore, multilateration method can be applied at closer applications which need more accurate positioning estimation.

مستخلص

تتكون أنظمة شبكات الحساس اللاسلكية من عدة نقاط حساسة تنتشر على مسافات متباعدة وتتعاون فيما بينها لمراقبة وجمع بيانات متعلقة بظاهرة فيزيائية أو بيئية محددة مثل درجة الحرارة، الحركة، الضغط والرطوبة، إن مواقع هذه الحساسات باتت موزعة بصورة عشوائية في منطقة الدراسة.

لمتابعة مواضع هذه النقاط "Localization" تم اقتراح عدد من الخوارزميات المعتمدة لتحديد مواقع الحساسات مع الأخذ في الاعتبار تقليل تكاليف العتاديات المستخدمة.

هناك نوعان من خوارزميات تحديد المواضع، النوع الأول هو خوارزميات تحديد الموضع المعتمدة على المدى والتي تتطلب مزيداً من العتاديات مما يزيد من كلفة التصميم للأنظمة، النوع الثاني خوارزميات غير معتمدة على المدى وهي مفيدة في تقليل كلفة العتاديات، بشكل عام هذه الخوارزميات تقدم دقة عالية في سيناريوهات مثالية، خوارزمية القفز بمعرفة منهجة المسافة "DV-hop" تعتبر من النوع الثاني وهي الأكثر استخداماً من بين خوارزميات هذا النوع.

هذه الرسالة تهدف إلى محاكاة خوارزمية القفز بمعرفة متجه المسافة لتحليل أدائها، حساب نسبة الخطأ المتوقعة ومحددات عمل الخوارزمية وذلك بناء على تطبيق أنظمة مختلفة لتوقع مكان الحساس والمفاضلة فيما بينها، أهم بارامتر هو متوسط الخطأ المطلق والذي تم عرضه في نتائج الدراسة.

تم الاستعانة ببرنامج ماتلاب لمحاكاة الأنظمة قيد الدراسة ومقارنة النتائج المتحصل عليها ودراسة حالات كل نظام حيث تظهر نتائج البحث متوسط الخطأ المطلق لطريقتي **multilateration** و **bounding box** أن صحة النتيجة في طريقة **multilateration** أعلى من **bounding box** وهو السبب الذي جعل كثيراً من الأنظمة تفضل استخدامها في التطبيقات التي تتطلب نتائج أقرب للصحة.

Abbreviations

ACK	Acknowledge
ADC	Analog to Digital Converter
AoA	Angle of Arrival
APIT	Approximate Point In triangulation
AWGN	additive White Gaussian Noise
CPE	Convex Position Estimation
CRLB	Cramer Ratio Lower Bound
dB	Decibel
DC	Direct Current
DME	Distance Measurement Error
DV	Distance Vector
FIM	Fisher Information Matrix
GPRS	General Packet Radio Service
GPS	Global Positioning System
HHA	Hybrid Hierarchical Architecture
IEEE	Institute of Electrical and Electronic Engineering
IR	Infrared
MAC	Media Access Control
MAE	Mean Absolute Error
MANET	Mobile Ad hoc Networks
NLOS	Non Line of Sight
PE	Position Error
PEB	Position Error Bound
RANs	Radio Access Networks

RF	Radio Frequency
RMS	Root Mean Square
RPE	Recursive Position Estimation Error
RSSI	Received Signal Strength Indicator
RTT	Round Trip time
SN	Sensor Node
SNR	Signal to Noise Ratio
TDoA	Time Difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
UMTS	Universal Mobile Telecommunication System
WiFi	Wireless Fidelity
WSN	Wireless Sensor Networks

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CHAPTER ONE

Introduction to thesis

1.1 Wireless Sensor networks Background.

Sensor networking is a multidisciplinary area that involves, among others, radio and networking, signals processing, artificial intelligence, database management, systems architectures for operator-friendly infrastructure administration, resource optimization, power management algorithms, and platform technology (hardware and software, such as operating systems). Sensors can be simple point elements or can be multipoint detection arrays. Each node in the sensor network can act as a repeater, thereby reducing the link range coverage required and, in turn, the transmission power.

Conventional wireless networks are generally designed with link ranges on the order of tens, hundreds, or thousands of miles.

Wireless Sensor Networks "WSNs" are similar to Mobile Ad hoc Networks (MANETs) in some ways; for example, both involve Multihop communications. [1]

However, the applications and technical requirements for the two systems are significantly different in several respects:

1. Sensor nodes use primarily *multicast or broadcast* communication, whereas most MANETs are based on point to point communications.
2. In most scenarios (applications) the sensors themselves *are not mobile* (although the sensed phenomena may be); this implies that the dynamics in the two types of networks are different.
3. Because the data being collected by multiple sensors are based on common phenomena, there is potentially a degree of *redundancy* in

the data being communicated by the various sources in WSNs; this is not generally the case in MANETs.

4. Because the data being collected by multiple sensors are based on common phenomena, there is potentially some *dependency* on traffic event generation in WSNs, such that some typical random-access protocol models may be inadequate at the queuing-analysis level; this is generally not the case in MANETs.
5. A critical resource constraint in WSNs is energy; this is not always the case in MANETs, where the communicating devices handled by human users can be replaced or recharged relatively often.
6. Number of sensor nodes in a sensor network can be several orders of magnitude higher than the nodes in a MANET.

For the above reasons the plethora of routing protocols that have been proposed for MANETs are not suitable for WSNs, and alternative approaches are required. [1]

1.2 Literature review.

Researchers see WSNs as an “exciting emerging domain of deeply networked systems of low-power wireless motes² with a tiny amount of CPU and memory, and large federated networks for high-resolution sensing of the environment. The field is now advancing under the push of recent technological advances and the pull of a myriad of potential applications. The radar networks used in air traffic control, the national electrical power grid, and nationwide weather stations deployed over a regular topographic mesh are all examples of early-deployment sensor networks; all of these systems, however, use specialized computers and communication protocols and consequently, are very expensive.

Much less expensive WSNs are now being planned for novel applications in physical security, health care, and commerce. Sensor networking is a multidisciplinary area that involves, among others, radio and networking, signal processing, artificial intelligence, database management, systems architectures for operator-friendly infrastructure administration, resource optimization, power management algorithms, and platform technology (hardware and software, such as operating systems).

A stated commercial goal is to develop complete micro electromechanical systems based sensor systems at a volume of 1 mm^3 . Sensors are internetworked via a series of Multihop short-distance low-power wireless links (particularly within a defined sensor field); they typically utilize the Internet or some other network for long-haul delivery of information to a point (or points) of final data aggregation and analysis. In general, within the sensor field, WSNs employ contention-oriented random-access channel sharing and transmission techniques that are now incorporated in the IEEE 802 family of standards; indeed, these techniques were originally developed in the late 1960s and 1970s expressly for wireless (not cabled) environments and for large sets of dispersed nodes with limited channel-management intelligence.

Conventional wireless networks are generally designed with link ranges on the order of tens, hundreds, or thousands of miles. The reduced link range and the compressed data payload in WSNs result in characteristic link budgets that differ from those of conventional systems. However, the power restrictions, along with the desire for low node cost, give rise to what developers call “profound design challenges”. Cooperative signal processing between nodes in proximity may enhance sensitivity and specificity to environmental event detection. [1]

1.3 Problem Statement.

Wireless sensors can be used where wire line systems cannot be deployed (e.g., a dangerous location or an area that might be contaminated with toxins or be subject to high temperatures).

In sensor networks, fine-grained time synchronization and localization are needed to detect events of interest in the environment under observation.

Location needs to be tracked both in local three-dimensional space (e.g., on what floor and in which quadrant is the smoke detected? What is the temperature of the atmosphere at height h ?) and over a broader topography, to assess detection levels across a related set (array) of sensors.

Localization is used for functionality such as beam forming for localization of target and events, geographical forwarding, and geographical addressing. [1]

In many such applications, each node requires location information to properly interpret its own sensor data and to act according to its placement in the world and in the network

Localization problem consists in finding accurate location of all unknown nodes in WSNs, which can be computed by a central unit or by sensor nodes. Localization systems are needed to:

- Report data that is geographically meaningful.
- Provide location stamps and locate and track point objects.
- Monitor the spatial evolution of a diffuse phenomenon
- Determine the quality of coverage.
- Achieve load balancing
- Form clusters

1.4 Research Objectives.

The thesis aims at study the accuracy of localization algorithms through a localization technique such that sensors determine their own positions after their placement other objectives are to:

- Estimate an unknown nodes position based on previously known node position by using different estimation scenarios.
- Compare between the scenarios efficiency in position estimation.
- Develop a simulation scenario to evaluate the localization methods.

1.5 Methodology.

Theoretical study of IEEE 802.15.4, studying the localization methods used to determine the most sufficient method and present a detailed analysis comparing the various alternatives of localization systems.

Evaluate performance of the localization system through many simulation experiments.

There are many different possible platforms for simulation and testing of localization methods in WSNs to simulate the following localization scenarios:

- Position computation by using Iteration problem method.
- Position computation by using Bounding box method.
- Position computation by using Multilateration method.
- DV- Hop localization algorithm.

MATLAB software provides a fast and easy way to prototype applications and has nice visualization capabilities; so MATLAB is used in thesis simulations.

1.6 Thesis Outline.

Chapter One gives a brief introduction to thesis work (Wireless sensor networks and localization systems). **Chapter Two** introduce the localization problem and Position computation in wireless sensor networks. In **Chapter Three** the Localization algorithms in wireless sensor networks is discussed and simulation environment were introduced. **Chapter Four** shows the simulations results with the results discussion. In **Chapter Five** thesis Conclusion and Recommendations are given.

CHAPTER TWO

Localization Techniques

2.1 Localization system Architecture.

The Hybrid Hierarchical Architecture “HHA” represents a particular case of network architecture; it is strictly hierarchical with four levels, where the wireless nodes have some specified (and some unspecified) characteristics depending on the level they belong to.

HHA does not aim at being general; there might be other network architectures based on different paradigms and topologies that deserve similar attention. However, it is recognized that some of its features make it worthwhile considering the HHA as a realistic and innovative reference scenario. HHA is reported in Figure 2.1. [2]

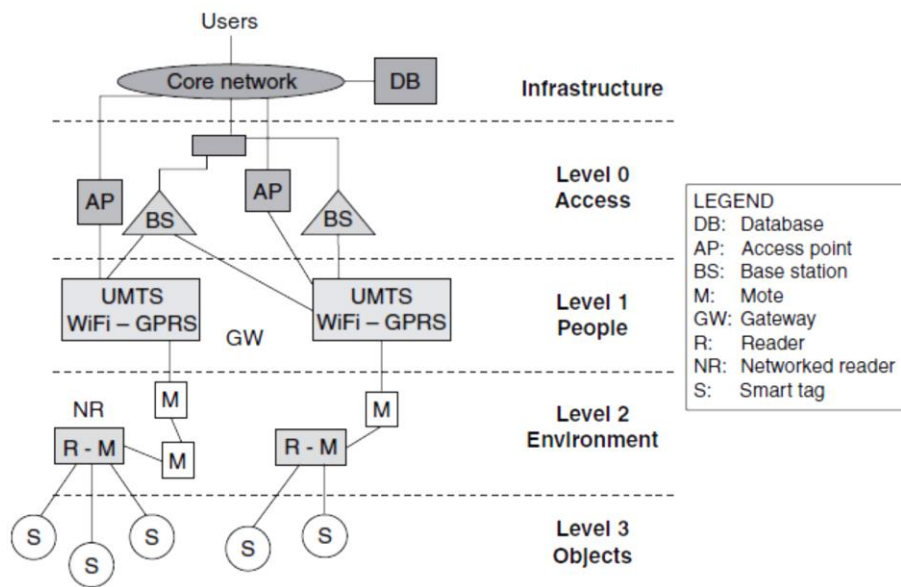


Figure 2.1 HHA for WSN's

At level zero, radio access ports (i.e., fixed stations covering the area through radio access networks (RANs) using air interface standards such as (GPRS or UMTS or Wi-Fi) provide access to mobile terminals (denoted here as mobile gateways, level one) usually carried by people.

The mobile devices can also be connected through a different air interface (e.g., Zigbee or Bluetooth) to a lower level of wireless nodes (level two) with limited energy and processing capabilities which can find access to the fixed network only through the gateways. [2]

Wireless nodes are distributed in the environment and provide information taken from it; they might be sensor nodes (SNs), or actuators or anchors providing localization data; moreover they interact through possibly different air interfaces with tiny devices at level three (e.g., smart tags or very-low-cost sensors) which are part of movable objects (e.g., printers, books, tickets, etc.).

This scenario defines a forest of (possibly disjointed) trees with heterogeneous radio interfaces at the different levels.

If the environmental level is connected through a tree-based topology, then the number of levels in the hierarchy further increases as level two is subdivided into sub-levels. [2]

2.1.1 Hybrid Hierarchical Architecture features.

The main features of HHA are:

- i. Heterogeneous:** different radio communication techniques are involved at the various interfaces between the levels (e.g., UMTS between 0 and 1 and Zigbee between 1 and 2) and also within a given level the nodes might use heterogeneous air interfaces (e.g., Bluetooth or Zigbee at level 2).
- ii. Hybrid:** the air interfaces and devices implement different communication paradigms (e.g., mesh or flat topologies) at the different levels.

- iii. **Nodes at level 1 are mobile gateways:** such as laptops or cellular phones carried by people and therefore are not specifically deployed for the aim of collecting data from the environment; rather, for cost reasons, these devices are exploited for such aims while used by people for their personal specific use (telephone conversations, web browsing, etc.).
- iv. **Multiple nodes with possible overlapping communication zones** are present at all levels.
- v. **Highly dynamic** because of the movement of nodes at two levels of the structure, namely levels 1 and 3.
- vi. **Based on a fixed hierarchy:** nodes at a given level can only attach to nodes at the immediate adjacent level. However, in some cases this feature might be removed. [2]

Basically, at each level it is recognized that the following main features characterizing or not the nodes:

1. Mobile or still.
2. Known or unknown locations.
3. Mesh, or tree, or absent topology connecting nodes within the level.
4. Coordinated planning or uncoordinated spatial distribution.
5. Strong or limited overlap of communication areas.
6. Different or similar communication capabilities at the two interfaces.
7. Strong, or weak, or absent energy constraints Global, or local or absent network node address.
8. Strong, or weak, or absent data processing capabilities. [2]

Clearly such features can significantly influence the selection of communication protocols and algorithms at the various air interfaces.

2.1.2 Sensing node components.

Figure 2.2 illustrate the components of a remote sensing node which includes the following:

- i. Sensing and actuation unit (single element or array).
- ii. Processing unit.
- iii. Communication unit.
- iv. Power unit.
- v. Other application-dependent units. [1]

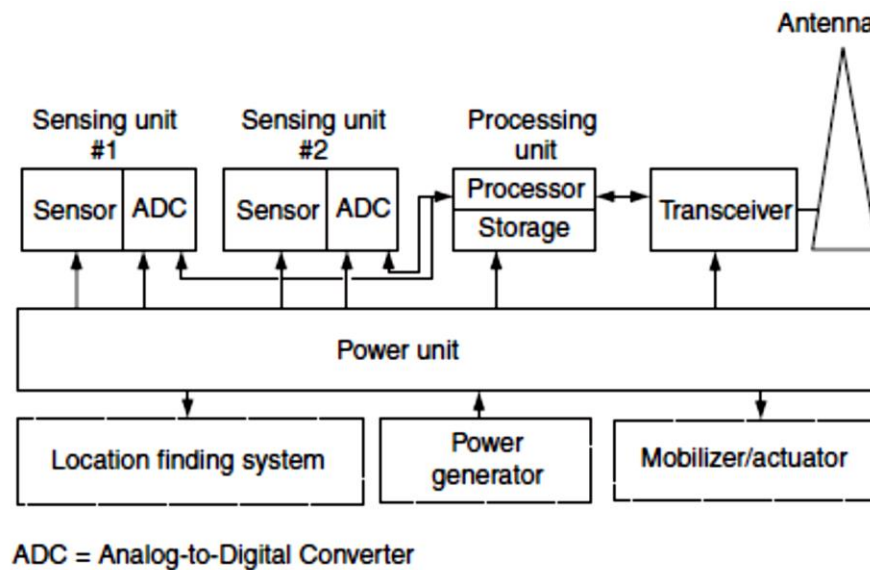


Figure 2.2 Typical sensor node

2.2 Localization Problem.

Localization of nodes is very crucial to find and determine location of sensor node with the help of specialized algorithm.

Localization is the process of finding the position of nodes as data and information are useless if the nodes have no idea of their geographical positions. [14]

For example, in a hospital, patients can be equipped with vital sign sensor nodes. These sensor nodes are able to measure and transmit the heart rate and blood oxygenation of patients as shown in Figure 2.3, through the

wireless network organized by these nodes, doctors can easily monitor the status of patients with a computer or a smart phone. Localization I needed to find the patients position.

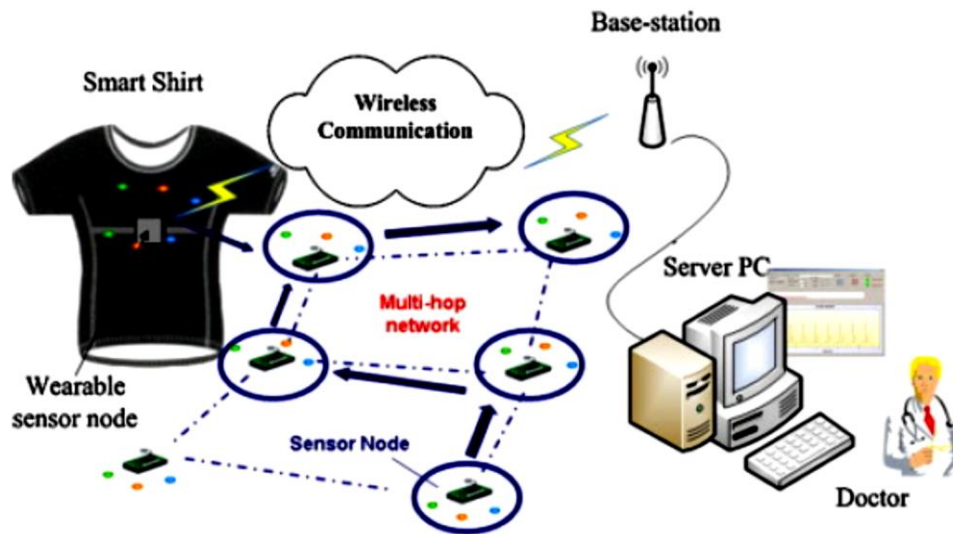


Figure 2.3 A Wireless Sensor Network for Hospital Monitoring

2.2.1 Localization vs. versa Global Positioning System (GPS).

Technologies using GPS have existed from some time now but most of the solutions only work in outdoor scenarios.

Localization indoors involves many more difficulties and represents an unsolved problem in many cases, especially when relative positioning to others and to objects is required while in movement. [3]

Other disadvantage is that GPS system is expensive, consumes too much power and has big size.

For outdoor localization the GPS is the most used system today, not only to retrieve position information but also as a reference base time source.

Unfortunately, battery drain, cost and size constraints preclude the utilization of GPS for several of the nodes in many WSN applications. Moreover, in indoor or cluttered environments its use is precluded entirely.

Depending on application constraints, only a small fraction of nodes might be equipped with GPS or are placed in known positions (anchor nodes or beacons).

The other nodes with unknown position are referred to as unknown nodes or agents) and must estimate their position by interacting with the anchor nodes.

As will be shown later, when a direct interaction with a sufficient number of anchor nodes is possible, single-hop algorithms can be adopted. Otherwise, cooperation between nodes is required to propagate, in a multi-hop fashion, the anchor node positions information to those nodes which cannot establish a direct interaction with anchor nodes. [3]

2.2.2 Designate the state of nodes.

A WSN can be composed of n nodes with a communication range of r , distributed in a two dimensional squared sensor field $Q = [0, s] \times [0, s]$.

For the sake of simplification, a symmetric communication link considered; that is, for any two nodes u and v , u reaches v if and only if v reaches u and with the same signal strength w . Thus, the network represented by the Euclidean graph $G = (V, E)$ with following properties:

- $V = \{v_1, v_2, \dots, v_n, \}$ is the set of sensor nodes.
- $\langle i, j \rangle \in E$ if v_i reaches v_j ; that is, the distance between v_i and v_j is less than r .
- $w(e) \leq r$ is the weight of edge $e = \langle i, j \rangle$.
- d is the distance between v_i and v_j . [13]

Some terms can be used to designate the state of a node:

1. **Unknown Nodes “U”:** Also known as *free* or *dumb* nodes, this term refers to the nodes of the network that do not know their localization

information. To allow these nodes to estimate their positions is the main goal of a localization system.

2. **Settled Nodes “S”**: These nodes were initially unknown nodes that managed to estimate their positions by using the localization system. The number of settled nodes and the estimated position error of these nodes are the main parameters for determining the quality of a localization system.
3. **Beacon Nodes “B”**: Also known as *landmarks* or *anchors*, these are the nodes that do not need a localization system in order to estimate their physical positions. Their localization is obtained by manual placement or external means such as GPS. These nodes form the base of most localization systems for WSNs.

The localization problem can then be defined as a Given a multi-hop network $G = (V, E)$ and a set of anchor nodes B their positions (x_b, y_b) , for all $b \in B$, we want to find the position (x_u, y_u) of as many $u \in U$ as possible, transforming these unknown nodes into settled nodes, S , figure 2.4 illustrate a simple example of the localization problem. [13]

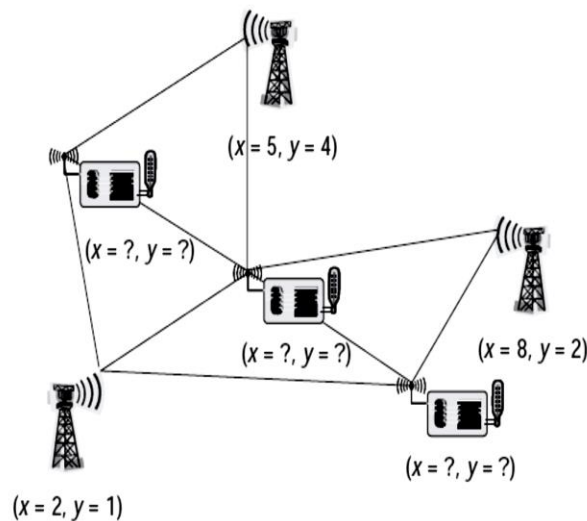


Figure 2.4 Simple example for localization problem

2.3 Localization system architecture.

Figure 2.5 present a typical model for the localization systems, the localization system can be divided into three distinct components:

- i. Distance estimation:** This component is responsible for estimating information about the distances between two nodes. This information will be used by the other components of the localization system.
- ii. Position computation:** This component is responsible for computing a node's position based on available information concerning distances/angles and positions of reference nodes (anchors).
- iii. Localization algorithm:** This is main component of a localization system. It determines how the available information will be manipulated in order to allow most or all of the nodes of a WSN to estimate their positions.

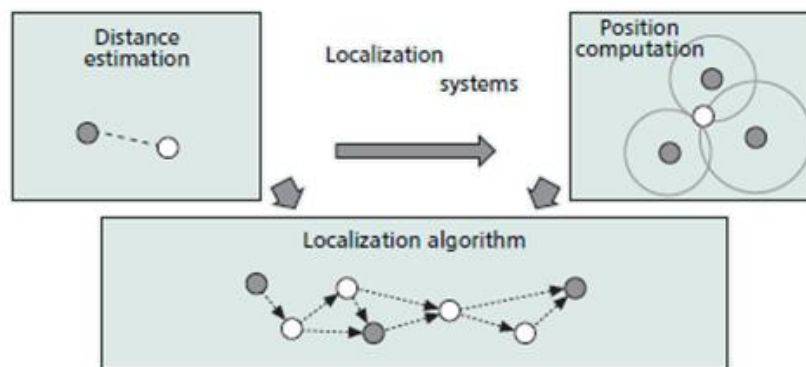


Figure 2.5 Localization system model [4]

The importance of such a division into components comes from the need to recognize that the final performance of the localization systems depends directly on each one of these components. [4]

Also, each component has its own goal and methods of solution. Subareas of the localization problem need to be separately analyzed and studied.

The Generic approaches of using anchor nodes are:

1. Determine the distances between regular nodes and anchor nodes. (Communication).
2. Derive the position of each node from its anchor distances. (Computation).
3. Iteratively refine node positions using range information and positions of neighboring nodes (Algorithm).

2.4 Measurement techniques.

2.4.1 Time measurement.

Usually, nodes are equipped with a local oscillator from which an internal clock reference is derived to measure the real time t . unfortunately; all oscillators are subjected to frequency drifts due to various physical effects as shown in Figure 2.6. Hence, only an estimation $\hat{t} = C(t)$ of the real time t can be obtained.[2]

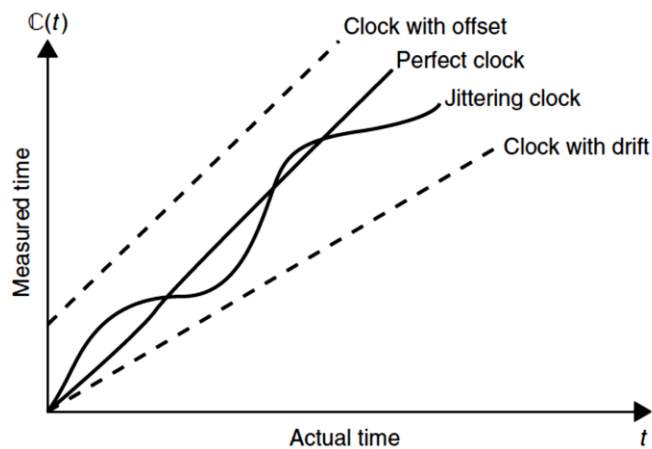


Figure 2.6 Relationship between the estimated and actual times [2]

The frequency of an oscillator changes over the time; however it can be approximated with good accuracy to be constant if the time intervals under measurement are small. In this case

$$C(t) = (1 + \delta)t + \mu \quad (2.1)$$

δ is the *clock drift* relative to the correct rate and μ is the *clock offset*.

The rate of a perfect clock, $dC(t)/dt$ would equal 1 (i.e., $\delta=0$).

The clock performance is often expressed in terms of part per million (*ppm*), defined as the maximum number of extra (or missed) clock counts over a total of 10^6 counts, that is, $\delta \times 10^6$

Supposing a node has to generate a time delay of τ_d seconds, the effective generated delay τ_{def} in the presence of a clock drift given by:

$$\tau_{\text{def}} = \frac{\tau_d}{1 + \delta} \quad (2.2)$$

In case a node has to measure a time interval of true duration $\tau = t_2 - t_1$ seconds, the corresponding estimated value $\hat{\tau}$ would be:

$$\hat{\tau} = C(t_2) - C(t_1) = \tau(1 + \delta) \quad (2.3)$$

In both cases there is no dependence on the clock offset “ μ ”.

Consider two nodes, whose oscillators will run at slightly different frequencies, causing the clock values to gradually diverge from each other. This divergence is called *clock skew*.

Network synchronization algorithms try to correct the *clock skew* by exchanging messages. [2]

2.4.2 Distance measurement.

Positioning techniques are based on measurement of certain physical quantities from which, mainly, the final position estimation accuracy and system complexity depend.

According to the nodes hardware capabilities, different kinds of measurements can be available based on radio frequencies (RF), direct current (DC) electromagnetic field, infrared (IR) and ultrasound. [2]

2.5 distance/angles estimation.

The simplest way to obtain useful measurements for positioning is *proximity* where the mere connectivity information is used to estimate node position.

The key advantage of this technique is that it does not require any dedicated hardware and time synchronization among nodes since the connection information is almost available in wireless devices. [2]

Making the common assumption that nodes are randomly located in the Poisson plane in the presence of a deterministic propagation scenario, where r_0 is the transmission range corresponding to a certain maximum tolerable path loss L_{th} .

The connection event between a pair of nodes A and B changes the probability distribution of the distance between a pair of connected nodes, which can be written as:

$$f_R(r) = \frac{2r}{r_0^2} \quad (2.4)$$

For $0 \leq r \leq r_0$ and 0 otherwise. [2]

2.5.1 Received Signal Strength Indicator (RSSI).

Based on the consideration that, in general, the further away the node; the weaker the received signal, it is possible to obtain an estimate of the distance between two nodes (ranging) by measuring RSSI.

Theoretical and empirical models are used to translate the difference (in dB) between the transmitted signal strength (assumed known) and the received signal strength into a range estimate. RSSI ranging does not require time synchronization between nodes. Figure 2.7 illustrate an example of RSSI. [2]

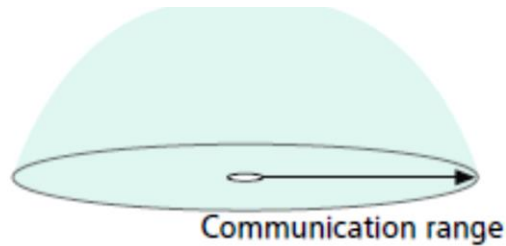


Figure 2.7 Decrease of signal strength

Generally, propagation effects cause small-scale slow and fast fading components. For ranging the extraction of only large-scale fluctuations are desirable. With wideband signals the mean received power can be calculated by summing the powers of the multipath in the power delay profile.

With narrowband signals, received power experiences large fluctuations over a local area and averaging should be used to estimate the mean received power.

Unfortunately, signal issues such as refraction, shadowing and multipath cause the attenuation to correlate poorly with distance resulting in inaccurate and imprecise distance estimates. Given a function correlating attenuation and distance, it is possible to estimate the distance between two nodes by measuring the strength of the signal. [2]

The widely used radio propagation model is the log-distance path loss model (without multipath effects):

$$RSSI(d)[dBm] = RSSI_{ref} - 10\alpha \log_{10}\left(\frac{d}{d_{ref}}\right) \quad (2.5)$$

RSSI is measured in *dBm*, which is a logarithmic measurement of signal strength,

d is the distance between emitter and receiver.

RSSI_{ref} is the signal strength value at reference distance d_{ref} . **α** is the attenuation constant (rate at which the signal decays).

Usually, α is obtained through empirical data. α is around 2 in a free-space environment, but its value increases if the environment is more complex (walls, large metallic objects, etc.).

In environments with many obstructions such as an indoor office space, an approximation of α is between 3 and 6. [2]

Based on Equation (2.5), a commonly used model for calculating the distance d is given by:

$$d = 10^{\frac{RSSI_{ref} - RSSI}{10\alpha}} \quad (2.6)$$

Where $RSSI_{ref}$ is measured at $d_{ref} = 1$ m.

Usually statistical model represented the log-normal shadowing effect is adopted. In this case the Cramer-Rao Lower Bound (CRLB) for a distance estimate \hat{d} from RSSI measurements provides the following inequality related to the estimate variance.

$$Var(\hat{d}) \geq \frac{d^2 \cdot \sigma^2}{(10\alpha / \ln 10)^2} \quad (2.7)$$

Where d is the distance between the two nodes and σ is the spread factor for the shadowing phenomena.

It can be observed that the best achievable limit depends only on channel parameters and not on the signal characteristics. [2]

2.5.2 Time of Arrival (ToA).

Considering that the electromagnetic waves travel at the light speed ($c = 3 \times 10^8$ m/sec) as in figure 2.8.

The distance information between a couple of nodes A and B can be obtained from the measurement of the propagation delay or time of flight (ToF). [5]

$$\tau_p = d/c = |t_a - t_b| \quad (2.8)$$

Where d is the actual distance between A and B. [2]

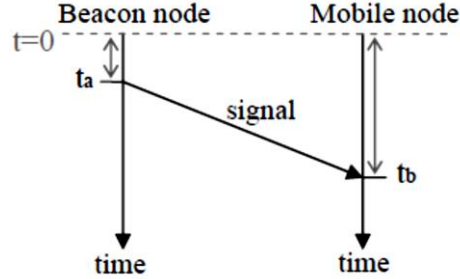


Figure 2.8 distance calculation of ToF in synchronized network

2.5.2.1 One way ranging scheme.

In a first simple scheme (*one-way ranging*), node A emits at time t_1 a packet to a receiving node B . The packet contains the timestamp t_1 at which the transmission started. Node B receives the packet at time t_2 . If the nodes were perfectly synchronized to a common reference clock (i.e., sharing the same time reference and time base), it is clear that τ_p would be calculated at node B as $\tau_p = t_2 - t_1$ and the distance estimated. [2]

Considering the more realistic case where nodes are not perfectly synchronized.

Suppose that node A and B have clock drifts δ_A, δ_B and offsets μ_A, μ_B , respectively. According to node A 's local time, the packet is transmitted at time $t_1^{(A)} = C_A(t_1)$ (included as a timestamp in the packet) and it is received at node B 's local time $t_2^{(B)} = C_B(t_2)$. Node B calculates the estimated propagation delay as:

$$\begin{aligned} \hat{\tau}_p &= t_2^{(B)} - t_1^{(A)} \\ &= \tau_p(1 + \delta_A) + t_2(\delta_B - \delta_A) + \mu_B - \mu_a \end{aligned} \quad (2.9)$$

As can be noticed in above equation, $\hat{\tau}_p$ could be significantly different from the true value τ_p if stringent synchronization constraints are not satisfied as happen in many practical cases. This problem becomes negligible when ultrasound devices are adopted.

Considering that the acoustic waves propagation speed (≈ 340 m/sec) is much lower than the light speed, synchronization errors can be several orders of magnitude smaller than the typical propagation delay values, making this technique very attractive for some specific applications. [2]

2.5.2.2 Two way ranging scheme.

A second scheme which supported by IEEE standard 802.15.4a requires less stringent synchronization constraints is two way ranging, figure 2.9 shows this scheme.

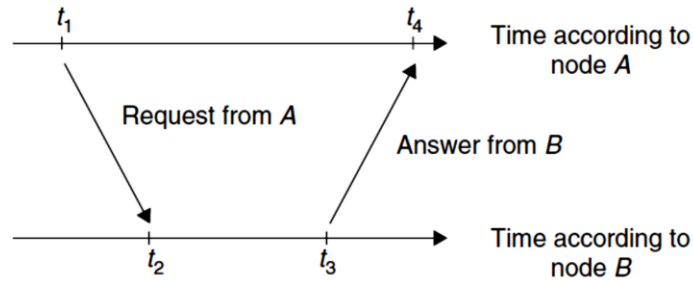


Figure 2.9 Two way ranging between two nodes

In this scheme node A emits a packet to node B which, after a response delay τ_d gives an answer by transmitting back a second acknowledge (ACK) packet to node A.

The round trip time (RTT) between the node A transmission and response receiving instants is:

$$RTT = 2\tau_p + \tau_d \quad (2.10)$$

Starting from the measurement of the RTT it is possible to estimate the distance d between node A and B . In this case clocks are not required to have the same time reference.

Since the effect of different *clock offsets* is eliminated by the difference operation. [2]

However, relative *clock drifts* still affect the ranging accuracy. In fact, with reference to (2.1) and (2.2), the effective response delay introduced by node B is $\tau_d/(1 + \delta_B)$, whereas the estimated RTT according to node A 's time scale is:

$$\widehat{RTT} = 2\tau_p(1 + \delta_A) + \frac{\tau_d(1 + \delta_A)}{(1 + \delta_B)} \quad (2.11)$$

In the absence of other information, node A derives the estimation of the propagation time $\hat{\tau}_p$.

Equating (2.11) with the supposed round-trip time $2\hat{\tau}_p + \tau_d$ leading to:

$$\hat{\tau}_p = \tau_p(1 + \delta_A) + \frac{\tau_d(\delta_A - \delta_B)}{2(1 + \delta_B)} \quad (2.12)$$

Defining $\epsilon = \delta_A - \delta_B$, the error on ranging estimate is:

$$\hat{\tau}_p - \tau_p = \tau_p\delta_A + \frac{\epsilon \tau_d}{2(1 + \delta_A - \epsilon)} \quad (2.13)$$

The accuracy obtained in RTT measuring can be reduced by adopting high precision oscillators or by adopting suitable time synchronization techniques but implemented at MAC level to avoid further delays at upper protocol layers.

In the above ranging error derivation, a perfect detection and estimation of the packet ToA has been implicitly assumed.

The detection of the exact arrival time of the transmitted packet in the presence of noise and multipath is a challenging problem that could significantly degrade the ranging error. [2]

2.5.3 Time Difference of Arrival (TDoA).

Time difference of Arrival (TDoA) is based on two schemes:

- i. The difference in the times at which a single signal from a single node arrives at three or more nodes.
- ii. The difference in the times at which multiple signals from a single node arrive at another node. [5]

2.5.3.1 Single signal from a single node.

Figure 2.10 shows the first scheme, in this scheme multiple signals are broadcasted from synchronized nodes at distinct known locations.

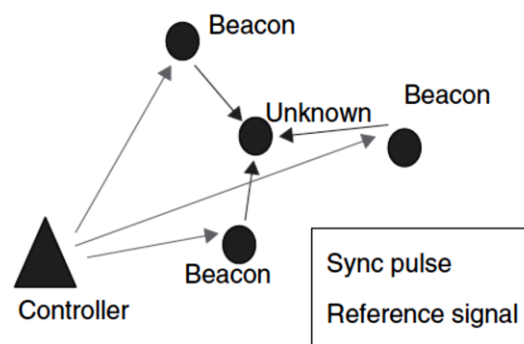


Figure 2.10 TDoA scheme 1

The receiver with unknown position measures TDoA and solves for the ToF. This technique is the same adopted by GPS. [2]

2.5.3.2 Multiple signals from a single node.

In a second scheme as shown in figure 2.11, a reference signal is broadcasted from the unknown node and received at several known locations with synchronized receivers (anchor nodes).

The receivers share their estimated ToA times, compute the TDoA, and solve for the ToF. Typically, receivers are synchronized through a wired network connection. [2]

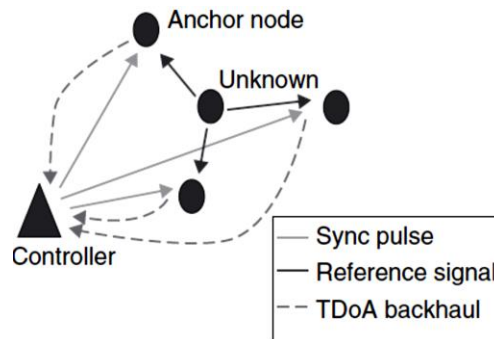


Figure 2.11 TDoA scheme 2

To calculate the position of the unknown node, at least three anchors with known position and two TDoA measurements are at least required.

A typical approach uses a geometric interpretation to calculate the intersection of two or more hyperbolas.

In fact, each sensor pair gives a hyperbola which represents the set of points at a constant range difference (time-difference) from two sensors. [2]

2.5.4 Angle of Arrival (AoA).

Instead of providing information about distance among nodes, angle-of-arrival measurements provide the information about node direction with respect to neighboring nodes.

The AoA on an incoming radio signal can be estimated by using multiple antennas with known separation (antenna array) and measuring the ToA of the signal at each antenna.

Given the differences in arrival times and the array geometry, it is possible to estimate the direction of propagation of a radio-frequency wave incident on the antenna array. [2]

To perform localization with AOA, two angle measurements are required, as shown in Figure 2.12.

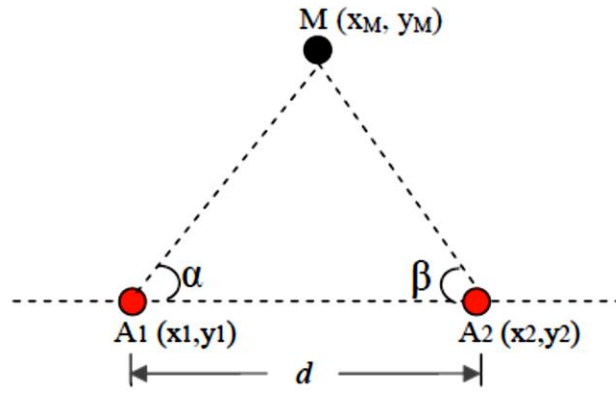


Figure 2.12 example of localization using AoA

The signal sending from the mobile node M is received by anchor A_1 and anchor A_2 . The antenna array of A_1 can detect the signal's AoA denoted as α , while A_2 can measure the AoA as β .

Then the two anchors send to M the angle information α and β as well as their positions (x_1, y_1) and (x_2, y_2) .

From the positions of anchors, M can calculate the distance between anchors, denoted as d . [2]

Finally, M estimates its position (x_M, y_M) through the triangulation approach by solving following equation. For simplicity, assume that A_1 and A_2 are on x-axis, that means, $y_1 = y_2$.

$$(x_M, y_M) = \begin{cases} x_M = x_1 + \frac{d \sin \alpha \sin \beta}{\sin(\alpha + \beta)} \\ y_M = \frac{d \cos \alpha \sin \beta}{\sin(\alpha + \beta)} \end{cases} \quad (2.14)$$

AoA does not require the precise time synchronization needed for ToA and TDoA techniques. Two angle measurements are required to determine node position (triangulation).

In NLOS environments, the measured AoA might not correspond to the direct path component of the received signal and large angle estimation errors can occur.

Due to the presence of multiple antenna elements, AoA techniques could be too expensive in terms of cost and device dimensions for WSN applications and require extensive signal processing. Also, the accuracy of AoA measurements is affected by a combination of factors, including multi-path reflections and background noise. This shall lead to large errors in angle estimation. [5]

2.5.5 Comparison between estimation methods.

Table 2.1 below shows a comparison of the Methods Used to Estimate Distances/Angles between Two Nodes. This comparison was a result of the paper [14].

Table 2.1 comparison between estimation methods

Method	Precision	Maximum distance	Extra Hardware	Challenges
RSSI	Meters (2-4m)	Communication range	None	Variation of the RSSI interfaces
ToA	Centimeters (2-3cm)	Communication range	None	Nodes Synchronization
TDoA	Centimeters (2-3cm)	Few meters (2-10m)	Ultrasound transmitter	Maximum Distance of work
AoA	A few degrees (5°)	Communication range	Set of receivers	Work on small sensors nodes

The chosen method depends on the application, scenario, and available resources. [2]

CHAPTER THREE

Localization Algorithms

3.1 Position Estimation.

The purpose of any positioning algorithm is given a set of measurements (e.g., distance, angle, connectivity) to find the locations of the nodes with unknown positions (unknown nodes).

Positioning occurs in two steps. First nodes measurements are obtained, then the measurements are combined using positioning techniques to deduce the location on the unknown nodes. [6]

Localization schemes are classified as **anchor based** or **anchor free**, **centralized** or **distributed**, **GPS based** or **GPS free**, **fine grained** or **coarse grained**, **stationary** or **mobile sensor** nodes, and **range based** or **range free**. [14]

3.1.1 Anchor Based and Anchor Free mechanisms.

In anchor-based mechanisms, the positions of few nodes are known. Unlocalized nodes are localized by these known nodes positions.

Accuracy is highly depending on the number of anchor nodes. The distance estimate to anchors can be obtained by direct interaction (single-hop), or indirectly by means of intermediate nodes (multi-hop).

Anchor-free algorithms estimate relative positions (virtual coordinates) of nodes instead of computing absolute node positions [6].

3.1.2 Centralized and Distributed schemes.

In centralized schemes, all information is passed to one central point or node which is usually called “sink node or base station”.

Sink node computes position of nodes and forwards information to respected nodes. Computation cost of centralized based algorithm is decreased and it takes less energy as compared with computation at individual node.

In distributed schemes, sensors calculate and estimate their positions individually and directly communicate with anchor nodes.

There is no clustering in distributed schemes, and every node estimates its own position.

3.1.3 GPS Based and GPS Free schemes.

GPS-based schemes are very costly because GPS receiver has to be put on every node. Localization accuracy is very high as well.

GPS-free algorithms do not use GPS and they calculate the distance between the nodes relative to local network and are less costly as compared with GPS-based schemes.

Some nodes need to be localized through GPS which are called anchor nodes that initiate the localization process [19].

3.1.4 Coarse Grained and Fine Grained schemes.

Fine-grained localization schemes result when localization methods use features of received signal strength, while coarse-grained localization schemes result without using received signal strength.

3.1.5 Stationary and Mobile Sensor Nodes.

Localization algorithms are also designed according to field of sensor nodes in which they are deployed.

Some nodes are static in nature and are fixed at one place and the majority applications use static nodes. That is why many localization algorithms are designed for static nodes. Few applications use mobile sensor nodes, for which few mechanisms are designed [19].

3.1.6 Range-Free and Range-Based Localization.

Range-free methods use radio connectivity to communicate between nodes to infer their location.

In range-free schemes, distance measurement, angle of arrival, and special hardware are not used.

During these years, many range-free localization algorithms have been proposed. Among them, Centroid, Convex Position Estimation (CPE), approximate point-in-triangulation test (APIT), gradient algorithm and Distance Vector-Hop (DV-hop), Recursive position estimation (RPE) are well known algorithms.

Centroid and CPE algorithms require a normal node has at least three neighbor anchors, while DV-hop algorithm doesn't have this requirement.

In range-based methods measurements provide some sort of distance/angle information among nodes.

3.2 Single-hop localization.

In comparing different algorithms, typical performance indexes are:

1. **The precision:** related to the dispersion of the position estimation error, generally modeled by a Gaussian probability distribution.
2. **The accuracy:** the degree to which the random variation is centered on the true value.
3. **The robustness** of the algorithm to some errors, such as range measurement errors.
4. **The coverage:** the percentage of nodes with estimated position.

From a sufficient number of distance or angle measurements, the positions of nodes can be computed. Several methods can be used to compute the position of a node.

Such methods include:

1. Trilateration method.
2. Multilateration method.
3. Bounding box method.
4. Triangulation method.

3.2.1 Trilateration method.

Trilateration is the most basic and intuitive method. This method computes a node's position via the intersection of three circles, as depicted in Figure 3.1

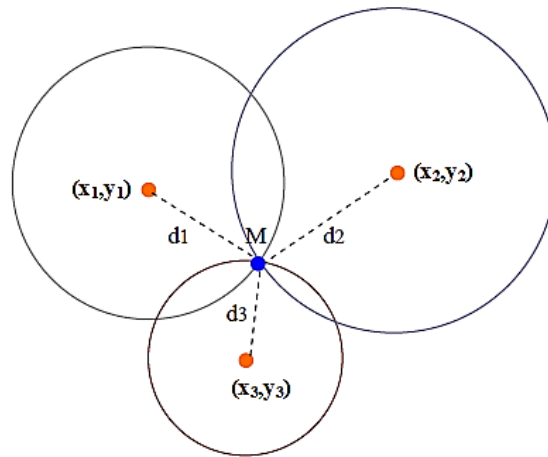


Figure 3.1 Theoretical model of trilateration

To estimate its position using trilateration, a node needs to know the positions of three reference nodes and its distance from each of these nodes. Distances can be estimated using one of the methods explained in the previous chapter.

In real-world applications the distance estimation inaccuracies as well as the inaccurate position information of reference nodes make it difficult to compute a position.

As depicted in Figure 3.2, the circles do not intersect at only one point, resulting in an infinite set of possible solutions. [8]

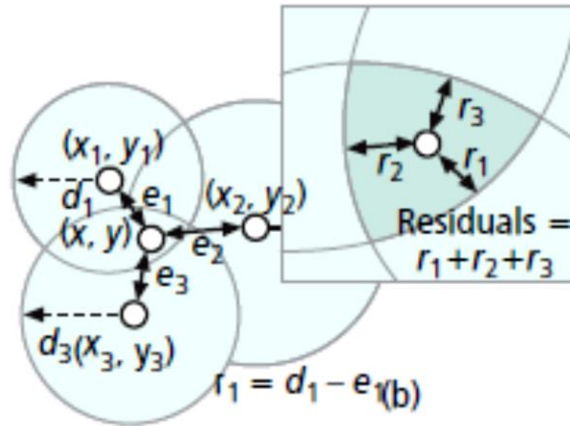


Figure 3.2 Realistic model of trilateration

3.2.2 Multilateration method.

When a larger number of reference points are available, multilateration method is used to compute the node's position.

In this case an over determined system of equations must be solved. Figure 3.3 depicts this case. [8]

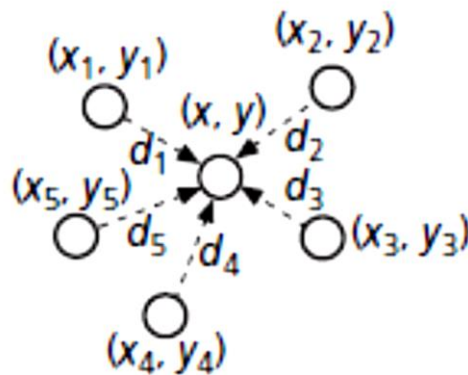


Figure 3.3 a model of multilateration

Figure 3.4 Considering the problem of determining the position (x, y) of an unknown node by using distance estimates d_i between the unknown node and a set of N anchor nodes placed at known coordinates (x_i, y_i) , with $i = 1, 2, \dots, N$. These estimates can be obtained, for example, through ToA or RSSI measurements. [10]

In the presence of ideal distance estimates, the i^{th} anchor defines a circle centered in (x_i, y_i) with radius d_i .

The intersection of the circles corresponds to the position of the target node. In a two-dimensional space, at least three anchors are required.

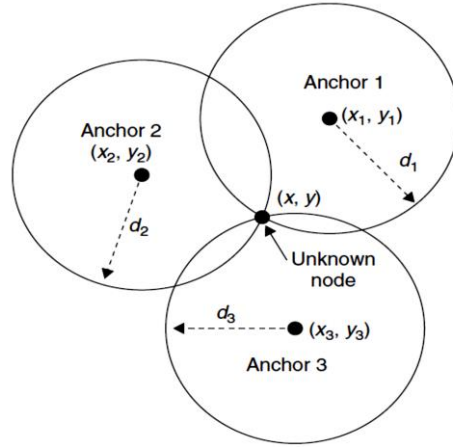


Figure 3.4 simple example of multilateration

More in detail, the position estimation can be obtained through the following system of equations:

$$\begin{aligned} (x_1 - x)^2 + (y_1 - y)^2 &= d_1^2 \\ &\vdots \\ (x_N - x)^2 + (y_N - y)^2 &= d_N^2 \end{aligned} \quad (3.1)$$

System (3.1) can be linearized by subtracting the last equation from the first N-1 equations, thus arriving at a proper system of linear equations given by the following matrix form:

$$A \times p = b \quad (3.2)$$

Where:

$$A \triangleq \begin{bmatrix} 2(x_1 - x_N) & 2(y_1 - y_N) \\ \vdots & \vdots \\ 2(x_{N-1} - x_N) & 2(y_{N-1} - y_N) \end{bmatrix} \quad (3.3)$$

$$b \triangleq \begin{bmatrix} x_1^2 - x_N^2 + y_1^2 - y_N^2 + d_N^2 - d_1^2 \\ \vdots \\ x_{N-1}^2 - x_N^2 + y_{N-1}^2 - y_N^2 + d_N^2 - d_{N-1}^2 \end{bmatrix} \quad (3.4)$$

and

$$p \triangleq \begin{pmatrix} x \\ y \end{pmatrix} \quad (3.5)$$

In a real scenario where estimation errors are present, equation (3.3) may be inconsistent, that is, circles do not intersect in one point.

When $N > 3$ the system of equations is over defined and it can be solved through a standard nonlinear least-square (LS) approach, that is,

$$\hat{p}^{(LS)} = (A^T A)^{-1} A^T b \quad (3.6)$$

With the assumption that $A^T A$ is non-singular, where superscript T denotes the transpose.

3.2.3 Bounding Box method.

Solving equation (3.6) is quite expensive since complex matrix floating point operations are required and often are not available in typical WSN devices. [8]

A much simpler method, presented as a part of the N -hop multi-iteration algorithm is Min-Max, also known as bounding box method, shown in figure 3.5 below.

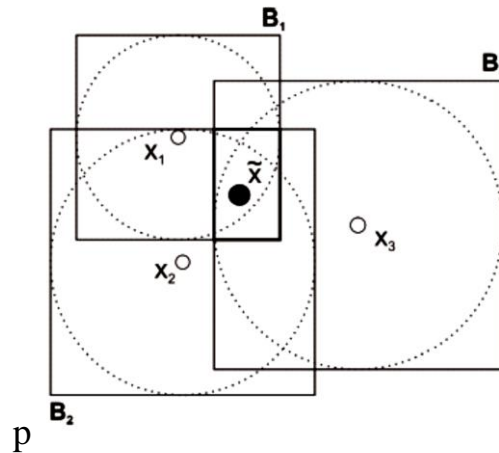


Figure 3.5 bounding box model

The idea is to construct a bounding box starting from each known position (x_i, y_i) and distance measurement d_i .

In particular, the bounding box corners of node i are

$$(x_i - d_i, y_i - d_i) \times (x_i + d_i, y_i + d_i) \quad (3.7)$$

The estimated position is obtained as the center of the intersection of these bounding boxes computed by taking the maximum of all coordinate minimums and the minimum of all maximums, that is,

$$\left[\max_i(x_i - d_i), \max_i(y_i - d_i), \right] \times \left[\min_i(x_i + d_i), \min_i(y_i + d_i), \right] \quad (3.8)$$

The final position is evaluated as the average of both corner coordinates.

$$(x_n, y_n) = \left(\frac{\max(x_i - d_i) + \min(x_i + d_i)}{2}, \frac{\max(y_i - d_i) + \min(y_i + d_i)}{2} \right) \quad (3.9)$$

The advantage of the Min-Max method is that it requires only low complexity sum and compare operations. [10]

Despite the final error of this method, which is greater than trilateration, computing the intersection of squares uses fewer processor resources than computing the intersection of circles.

3.2.4 Triangulation method.

In triangulation, shown in figure 3.6, information about angles is used instead of distances. Position computation can be done remotely or by the node itself; the latter is more common in WSNs.

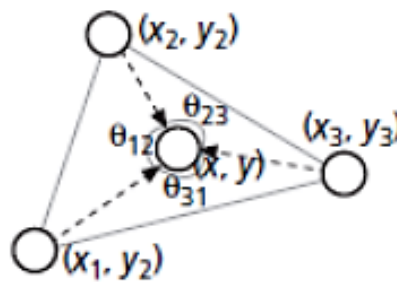


Figure 3.6 Triangulation model

At least three reference nodes are required. The unknown node estimates its angle to each of the three reference nodes and, based on these angles and the positions of the reference nodes (which form a triangle), computes its own position using simple trigonometrical relationships.

This technique is similar to trilateration. In fact, based on the AoAs, it is possible to derive the distances to reference nodes [8].

3.3 Accuracy in Localization systems.

3.3.1 Accuracy metric.

The basic goal of the localization accuracy metric is to show how will match the ground truth and estimated positions are. The simplest way to describe location performance is to determine the residual error between the estimated and actual nodes position.

For example, in AWGN the optimum ToA estimator is characterized by an asymptotic MSE given by the CRLB which is a decreasing function of the SNR.

The preceding discussion in this thesis has assumed an idea situation; however, distance estimation always contains errors that will, in turn, lead to location errors.

Distance measurement error (DME) is defined as the difference between actual and estimated distance between anchor nodes and unknown node as given by:

$$DME_i = |d_i - de_i| \quad (3.10)$$

Where de_i is estimated distance, d_i is the actual distance, DME_i is distance error, distance estimation always contains errors that will, in turn, lead to location errors. [5]

The residual value, as the mean of the distances error (differences between the estimated and actual distances) is represented in:

$$Residual\ Error = \sum_{i=1}^n DME_i \quad (3.11)$$

Where n is number of anchor nodes. The real challenge for methods of estimation position arises when the distance measurements are not perfect but only estimates de_i with a distance measurement error DME are known.

Range and distance measurements are degraded by both time-varying errors (such as noise or interference) and environment-dependent errors.

In reality distance estimation always constant errors that will, in turn, lead to location errors. [5]

Location or position error (PE) is defined as the difference between actual and estimated position of receiver as:

$$PE = \sqrt{(x_{actual} - x_{estimated})^2 + (y_{actual} - y_{estimated})^2} \quad (3.12)$$

The mean absolute error metric (MAE), as one of the mean accuracy metrics calculates the position error (PE) between the receiver's estimated and actual coordinates for each of n samples. This is shown in:

$$MAE = \frac{\sum_{i=1}^n PE_i}{n} \quad (3.13)$$

The resulting metric represents the average positional error and then aggregating individual residual errors into one statistic.

The MAE computation has much similarity to root mean square (RMS) error, a commonly used calculation to measure the difference (or residual) between predicted and observed values. [5]

3.3.2 Position Error Bound (PEB).

It is known from estimation theory that the ML estimation error tends asymptotically to the Gaussian distribution.

If we denote by d_i the true distance, the measured range r_i can be expressed as

$$r_i = d_i + \epsilon_i \quad (3.14)$$

Where ϵ_i is a random Gaussian noise with zero-mean and variance σ_i^2 accounting for the ranging estimation error. Modeling the dependence of the variance of ϵ_i on the distance d_i give:

$$\sigma_i^2 = \sigma^2(d_i) = \sigma_0^2 \alpha_i^n \quad (3.15)$$

α is the path loss exponent

σ_0^2 is the variance at 1 metre.

The position error bound (PEB) is a fundamental theoretical performance limit on the accuracy of any localization method. PEB calculated in the case where the measurements are assumed to be independent. PEB given by:

$$PEB(x, y) \triangleq \sqrt{T\{J^{-1}\}} \quad (3.16)$$

Where J is the Fisher information matrix (FIM).

$$J = \sum_{i=1}^N A(d_i)M(\theta_i) \quad (3.17)$$

Where θ_i is the angle between the unknown node and the i^{th} anchor node measured with respect to the horizontal.

$$M(\theta) \triangleq \begin{bmatrix} \cos^2\theta & \cos\theta \sin\theta \\ \sin\theta \cos\theta & \sin^2\theta \end{bmatrix} \quad (3.18)$$

And

$$A(d) \triangleq \frac{1}{\sigma^2(d)} + \frac{\sigma^2}{2d^2} \quad (3.19)$$

The expression (3.17) provides some useful insights. $M(\theta_i)$ contains geometric information about the relative position of the unknown node with respect to the i^{th} anchor node. These weights return the quality of the range measurements and thus capture how much new information each measurement brings. [10]

From (3.19) we see that when d goes to infinity (so that the range measurement variance goes to infinity) the weights $A(d_i)$ tend to zero. This is consistent that the larger the range estimation variance, the less valuable the corresponding range information will be in determining the unknown node's position.

The corresponding $M(\theta_i)$ in (3.17) will receive a low weight and the contribution from the i^{th} anchor node will be small.

The weights $A(d_i)$ therefore quantify the importance of the information coming from the i^{th} anchor node. This implies that the information from anchor nodes that are far away (large range measurement variance) will not contribute much to the FIM and the localization accuracy is mainly affected by local nodes. [10]

Using the analytical expression for the FIM to obtain the PEB. Since the FIM is a 2×2 matrix, its inverse is easily obtained and can be plugged into (3.19) to obtain:

$$PEB(x, y) = \sqrt{\frac{\sum_{i=1}^N A_i}{(\sum_{i=1}^N A_i c_i^2)(\sum_{i=1}^N A_i s_i^2) - (\sum_{i=1}^N A_i c_i s_i)^2}} \quad (3.20)$$

Where:

$$A_i \triangleq A(d_i)$$

$$c_i \triangleq \cos \theta_i$$

$$s_i \triangleq \sin \theta_i$$

Stress that the limit on the localization accuracy given in (3.20) depends on the distance between the unknown node and the anchor nodes.

For a practical system we may be interested in the quality of localization not just at one point, but over an area.

3.4 Localization algorithm

The localization algorithm is the main component of a localization system. This component determines how the information concerning distances and positions is manipulated in order to allow most or all of the nodes of a WSN to estimate their positions.

Localization algorithms classified into a few categories: [13]

1. Distributed or centralized.
2. Position computation; with or without an infrastructure.
3. Relative or absolute positioning.
4. Designed for indoor or outdoor scenarios.
5. One hop or Multihop.

This thesis discussion will concerned on Multihop localization algorithm.

3.5 Multihop localization.

Generally, a low number of anchor nodes is appreciated due to cost and feasibility constraints, hence single-hop localization could fail in cases of unknown nodes that are not able to interact with a sufficient number (at least three) of anchor nodes.

As a consequence, cooperation among nodes is required to estimate node positions through Multihop cooperative localization algorithms. As seen in figure 3.7, a common 3-phase structure is identified:

1. **Phase1:** Determine the distances between unknowns and anchor nodes.
2. **Phase2:** Derive for each node a position from its anchor distances (using, for example, multilateration or Min-Max algorithms).
3. **Phase3:** Refine the node positions using information about the distance to and positions of neighboring nodes.

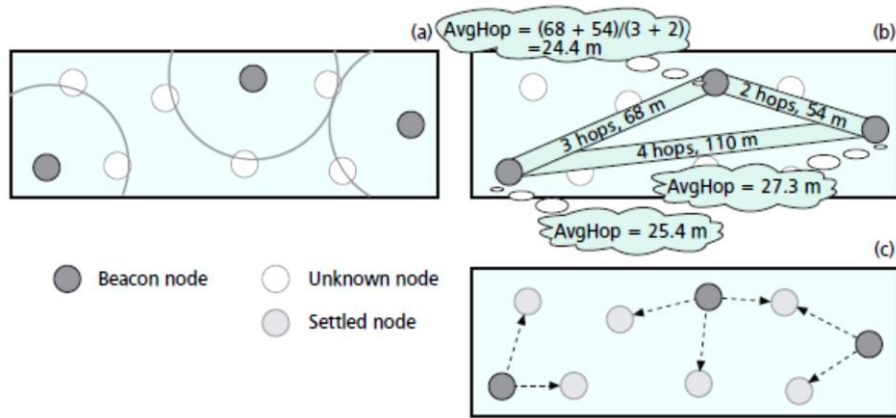


Figure 3.7 Multihop localization phases [10]

Another approach is to consider fully iterative distributed algorithms, where nodes surrounding anchor nodes cooperatively establish position estimates that are successively propagated to more distant nodes, allowing them to estimate their position without direct anchor node visibility.

At each iteration step, once a node with unknown position (x, y) bears N nodes with known or estimated positions, it would be able to estimate its position starting from the measured distances d_i and known positions (x_i, y_i) if $N \geq 3$. [10]

3.5.1 N-hop multilateration.

In the N-hop multilateration algorithm the distance to the anchors is simply determined by adding the ranges encountered at each hop during the network flood.

In particular, the anchors send an anchor message including their identity, position and path length accumulator set to 0.

Each receiving node adds the measured range from the previous node to the path length field and broadcasts the new message to the other nodes.

If multiple messages about the same anchor are received, the node keeps and forwards only the one containing the minimum value of path length.

One of the main disadvantages of this approach is that range errors accumulate over multiple hops. The cumulative error becomes significant in the presence of large networks with few anchors or poor ranging hardware (e.g., based on RSSI measurements).

3.5.2 DV-hop algorithm.

The DV-hop algorithm is similar to the N-hop multilateration.

Anchor packets are flooded by anchor nodes throughout the network.

Each receiving node maintains the minimum counter value per anchor node of all anchors it receives and ignores those anchors with higher hop-count values as done in the classical distance vector routing scheme.

In this way each node in the network has a rough distance information, in terms of hops, to every anchor node. To enable the conversion from number of hops and physical distance, anchor nodes evaluate the average single-hop distance, d_{hop} , starting from the hop count information and known position of all other anchors inside the network.

In particular, anchor node i estimates d_{hopi} using the following formula

$$d_{hopi} = \frac{\sum_j \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum_j h_{i,j}} \quad (3.21)$$

Where: (x_j, y_j) is the position of the j^{th} anchor node.

$h_{i,j}$ is the distance, in hops, from anchor i to anchor j .

Once calculated, anchors broadcast the estimated average hop size information. Unknown nodes can evaluate the estimated distance to anchor node i by multiplying the counted hops by the average hop size d_{hopi} .

Finally, those unknown nodes which obtain the distance estimation to at least three anchors can estimate their location by using multilateration (e.g., the simple Min-Max algorithm). [10]

To measure the accuracy of location, based on (3.13) the mean absolute error (MAE) is defined as:

$$MAE(x, y) = \frac{\sum_{i=1}^{UNAmount} \sqrt{(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2}}{UNAmount} / R \quad (3.22)$$

Where UNAmount is the number of the unknown nodes in the network. R is the communication radius of nodes.

An advantage of the DV-Hop is that its localization algorithm requires a low number of anchor nodes in order to work.

However, the way distances are propagated as well as the way these distances are converted from hops to meters in DV-Hop, result in erroneous position computation, which increases the final localization error of the system. [13]

3.5.3 Recursive Position Estimation algorithm (RPE).

In RPE nodes estimate their positions based on a set of initial anchor nodes (e.g., 5 percent of the nodes) using only local information.

Localization information increases iteratively as newly settled nodes become reference nodes.

The RPE algorithm can be divided into four phases, as depicted in Figure 3.8.

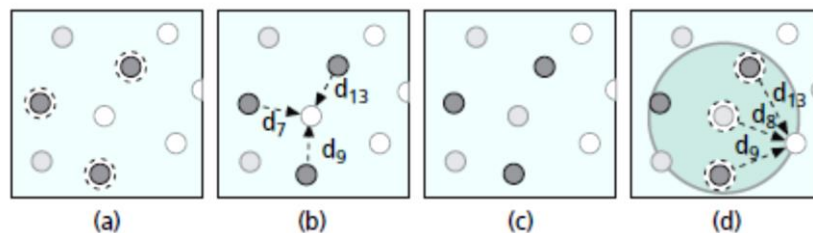


Figure 3.8 RPE localization phases

In the first phase a node determines its reference nodes. In the second phase the node estimates its distance to these reference nodes using, for example, RSSI.

In the third phase the node computes its position using trilateration (becoming a settled node). In the final phase the node becomes a reference node by broadcasting its newly estimated position to its neighbors.

When a node becomes a reference, it can assist other nodes in computing their positions as well.

3.5.4 DV-hop comparing to other algorithms.

Centroid and CPE algorithms require a normal node has at least three neighbor anchors, while DV-hop algorithm doesn't have this requirement.

However, these localization algorithms are not accurate enough, and they are usually studied without network context.

Other advantage of DV-hop algorithm is that the number of reference nodes increases quickly, in such a way that the majority of the nodes can compute their position. But this technique has the disadvantage of propagating localization errors.

This means that the inaccurate position estimation of one node can be used by other nodes to estimate their positions, increasing this inaccuracy.

Furthermore, a node must have at least three reference neighbors in order to compute its position.

3.6 System modeling.

The simulation programs have been written by MATLAB language script. MATLAB programs are stored as plain text in files having names that end with the extension ".m".

These files are called m-files. Each m-file contains exactly one MATLAB function. Thus, a collection of MATLAB functions can lead to a large number of relatively small files.

The difference between MATLAB and traditional high level languages is that MATLAB functions can be used interactively. In addition to providing the obvious support for interactive calculation, it also is a very convenient way to debug functions that are part of a bigger project.

3.6.1 Position estimation.

This simulation scripts aims to calculate the position Error (PE) and the Mean Absolute Error (MAE) which was introduced in equation (3.13) for the following cases:

1. Compare between *trilateration* and *bounding box* positioning estimation methods for 3 anchor nodes with the below situations:
 - i. Distance Measurement Error (DME) = 0 m (ideal situations).
 - ii. Distance Measurement Error (DME) < 3 m
 - iii. Distance Measurement Error (DME) \geq 3 m
 - iv. Compare DME vs. PE in a specific Communication range.

Based on measured GPS positioning values; an assumed anchor nodes positions (x_i, y_i) used are:

- $(x_1, y_1) = (95, 125)$
- $(x_2, y_2) = (90, 75)$
- $(x_3, y_3) = (60, 110)$

For the simulations purpose; Assumed actual position of the unknown node is $(x_u, y_u) = (80, 95)$. Figure 3.9 shows the simulation flow chart.

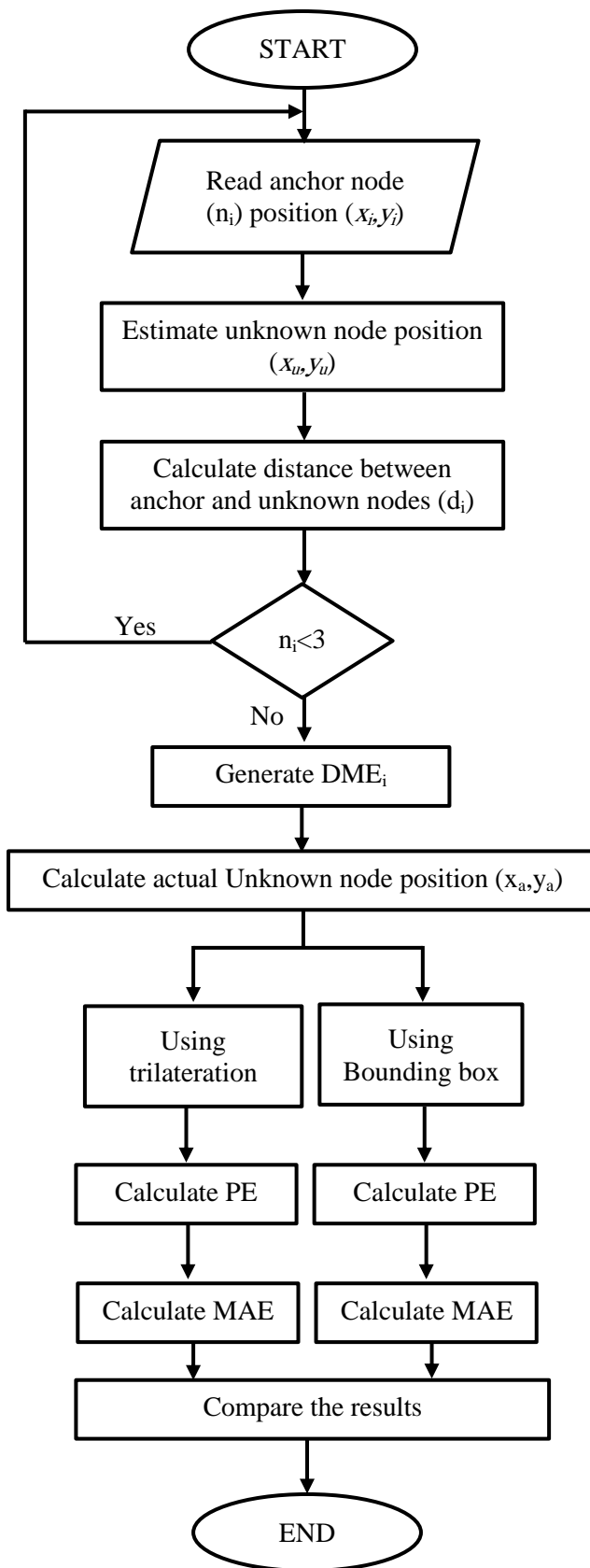


Figure 3.9 Position estimation flow chart for three nodes

2. Compare between *multilateration* and *bounding box* positioning estimation methods for four nodes with Distance Measurement Error (*DME*).

The assumed anchor nodes positions (x_i, y_i) are:

- $(x_1, y_1) = (95, 125)$.
- $(x_2, y_2) = (90, 75)$.
- $(x_3, y_3) = (60, 110)$.
- $(x_4, y_4) = (65, 75)$.

Also for this simulations; the assumed actual position of the unknown node is $(x_u, y_u) = (80, 95)$. Figure 3.10 shows the simulation flow chart.

The assumptions for above simulations are listed in table (3.1).

Table 3.1 Position estimation simulations assumption

Number of Samples	100 samples
Number of unknown nodes per sample	1 node
Samples distribution in deployed area	Random distribution
Radio Range distribution	from 10 to 100 m

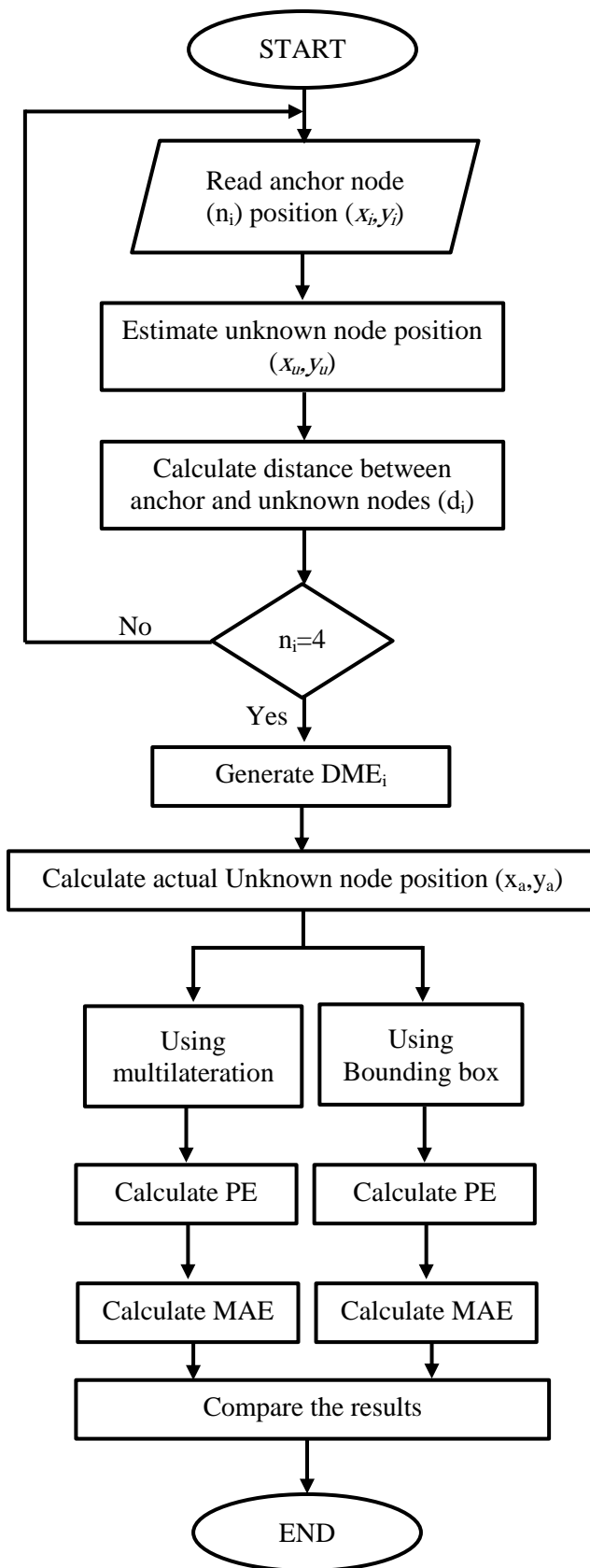


Figure 3.10 Position estimation flow chart for four nodes

3.6.2 DV-hop localization algorithm.

The aim of this simulation is to compare the mean absolute error (MAE) for the trilateration and bounding box localization methods when used in the DV-Hop algorithm. Figure 3.10 shows the flow chart of the above simulation.

The ideal radio propagation is assumed, with no signal loss, no interference occurred and no collisions.

The main assumptions of simulation scenario are shown in table (3.2)

Table 3.2 DV hop localization algorithm simulation assumptions

Simulation Area	$100 \times 100 \text{ m}^2$
Node communication range	20 m
Total Number of nodes	100 nodes
Number of anchors	8
Random times	$20 \times 100 = 2000$ times
nodes distribution in deployed area	Random distribution

Total number of nodes includes anchors and unknown nodes. The parameter “ratio of nodes” is defined as the ratio between number of anchor and total number of nodes.

The introduced metric used for measuring the accuracy of estimated distance is the deviation between the estimated distance and its real value.

The position error (PE) (% radio range) used to measure the accuracy of algorithms, which estimate the position of one normal node. However, in this simulation, many more normal nodes appear.

So there is need to use mean absolute location error (MAE) (% radio range)” to quantize the accuracy. This metric is calculated as the average of location errors from all normal nodes.

This simulation scripts aims to:

- i. Calculate the average hop distance for each node.
- ii. Locate the node hops information according to them own records in a data table calculation.
- iii. Estimate distance between each anchor nodes.

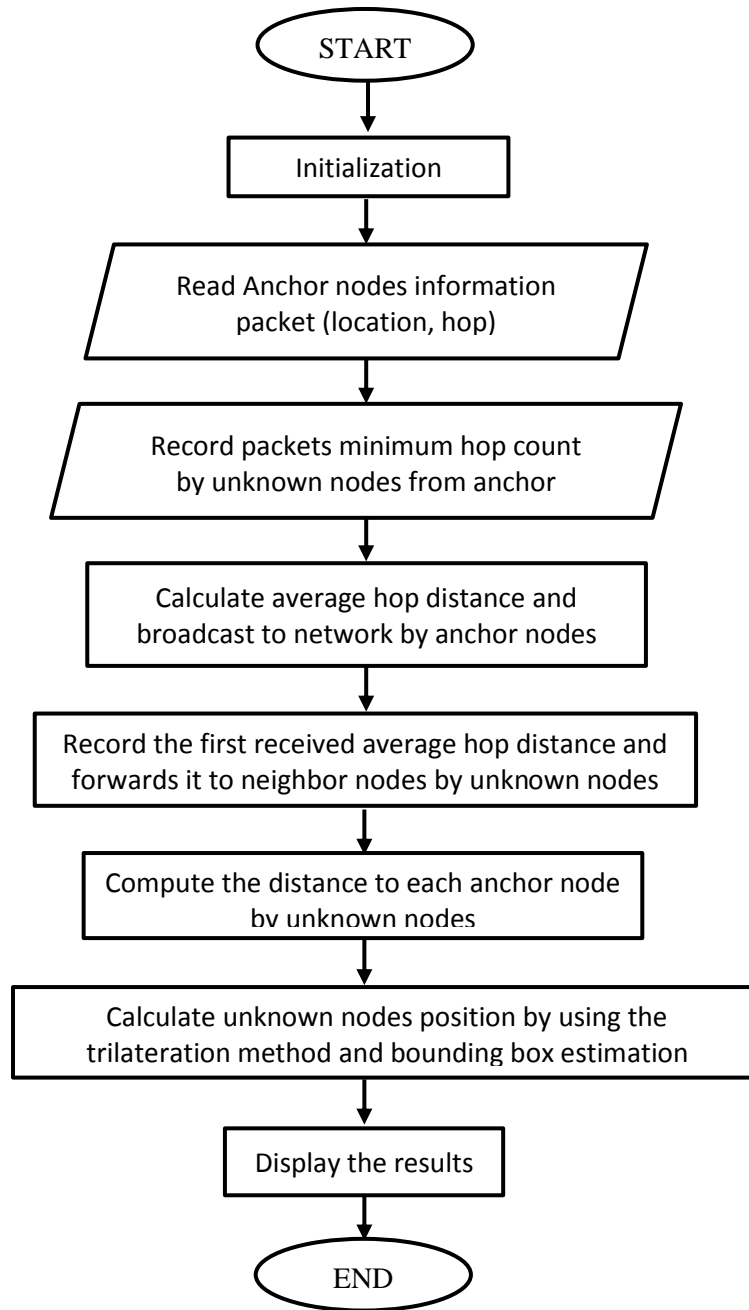


Figure 3.11: DV-hop localization algorithm flow chart

CHAPTER FOUR

Results and Discussion

4.1 Position Estimation results.

The below results are given by Matlab simulation based on figures (3.9) and (3.10) with aid of paragraph 3.6.1 scenario.

4.1.1 Iteration and bounding box with DME = 0m.

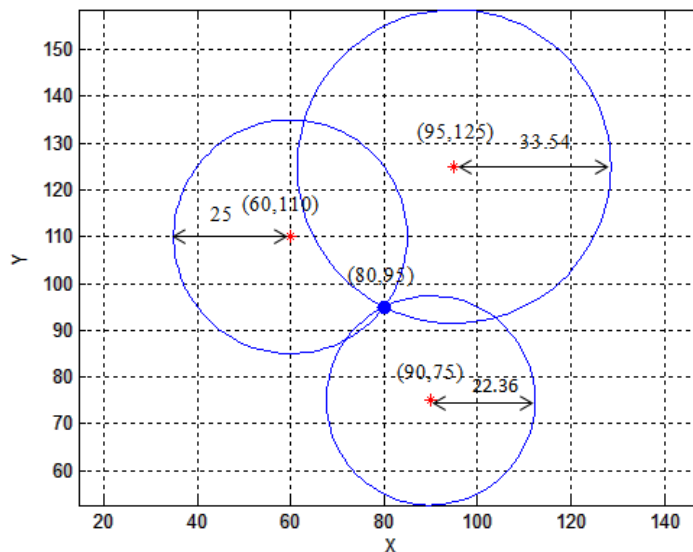


Figure 4.1: Estimating position for iteration method with DME=0

In this case the distance measurement error is assumed to be zero meters, which is an ideal situation. So the MATLAB program deploys the nodes randomly with correct distance measurement within the limits of the communication range (100m) and then it estimates the position using iteration position method.

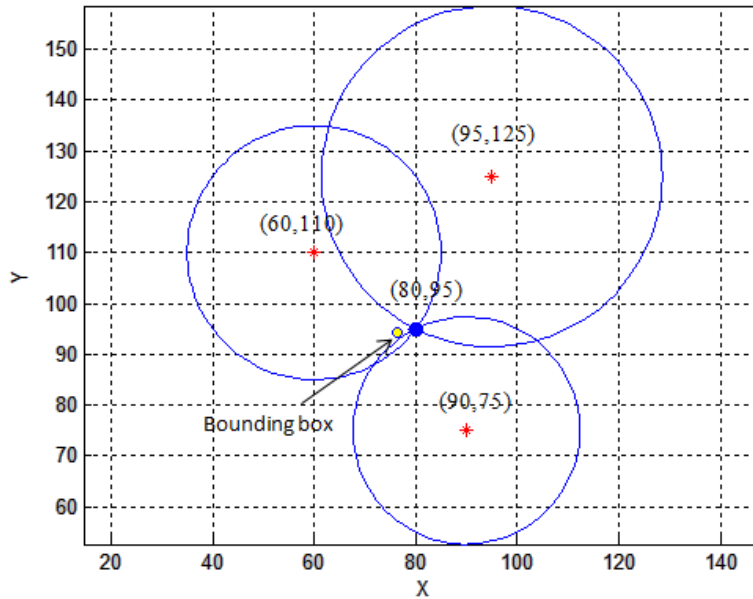


Figure 4.2: Estimating position for bounding box method with DME=0

In this case the distance measurement error is assumed to be zero meters, which is an ideal situation. So the MATLAB program deploys the nodes randomly with correct distance measurement within the limits of the communication range (100m) and then it estimates the position using bounding box positioning method. Table 4.1 compare between the two results discussed above.

Table 4.1: Trilateration and bounding box result with DME = 0

	Trilateration	Bounding box
Maximum Coordinates (x_{max}, y_{max})	-	(85, 97.36)
Minimum coordinates (x_{min}, y_{min})	-	(67.64, 91.46)
Unknown node position (x_u, y_u)	(80,95)	(76.32,94.41)
Position Error (PE)	0 m	3.727 m

4.1.2 Iteration and bounding box with DME < 3m

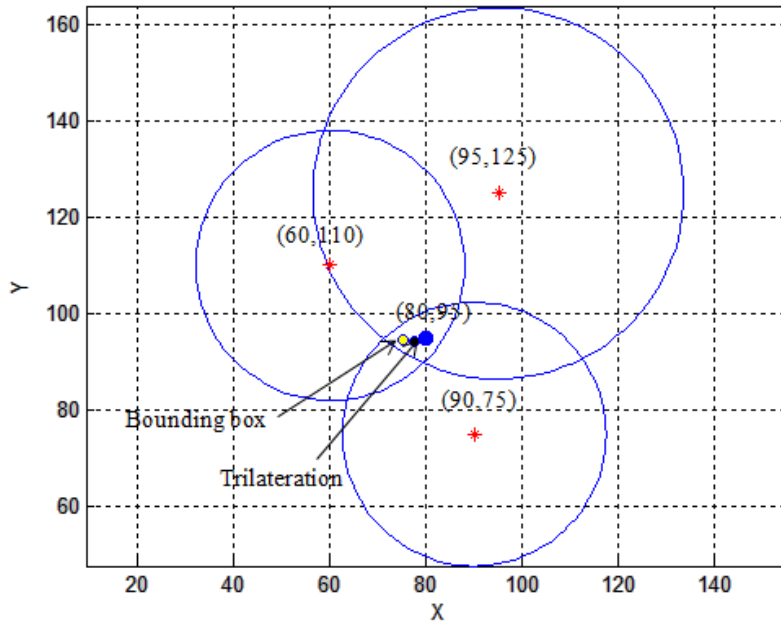


Figure 4.3: Estimated position of unknown node with DME < 3

In this case the distance measurement error is assumed to be less than three meters. So the MATLAB program deploys the nodes randomly with a less distance measurement error within the limits of the communication range (100m) and then it estimates the position using trilateration and bounding box positioning methods, the results are compared in table 4.2 below.

Table 4.2: Trilateration and bounding box results with DME < 3

	Trilateration	Bounding box
Maximum Coordinates (x_{max}, y_{max})	-	(88, 102.36)
Minimum coordinates (x_{min}, y_{min})	-	(62.64, 86.46)
Unknown node position (x_u, y_u)	(77.496, 94.133)	(75.32, 94.41)
Position Error (PE)	2.6504 m	4.717 m

4.1.3 Iteration and bounding box with DME $\geq 3m$.

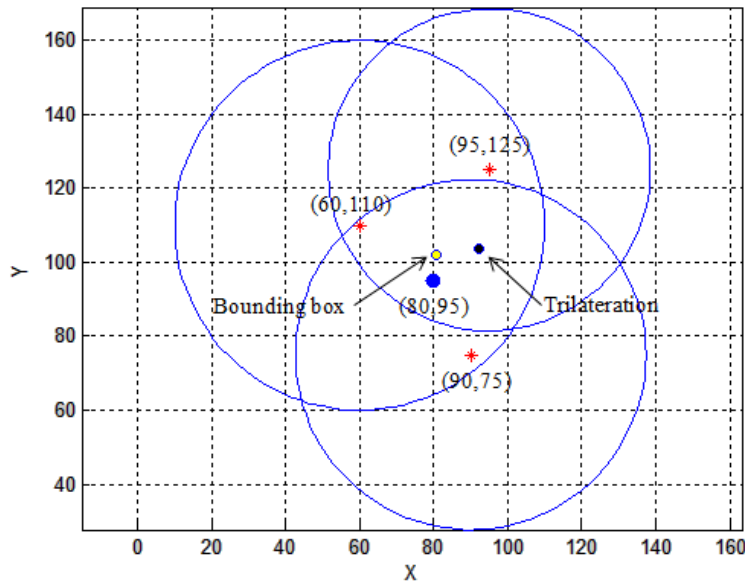


Figure 4.4: Estimated position of unknown node with DME ≥ 3

In this case the distance measurement error is assumed to be greater than or equal three meters. MATLAB program deploys the nodes randomly with a more distance measurement error within the limits of the communication range (100m) and then it estimates the position using trilateration and bounding box positioning methods, the results are compared in table 4.3 below.

Table 4.3: Trilateration and bounding box results with DME ≥ 3

	Trilateration	Bounding box
Maximum Coordinates (x_{max}, y_{max})	-	(110, 122.36)
Minimum coordinates (x_{min}, y_{min})	-	(51.46, 81.46)
Unknown node position (x_u, y_u)	(92.1283, 103.5095)	(80.73, 101.91)
Position Error (PE)	14.858 m	6.9485 m

4.2 Position Estimation for more than three anchors nodes.

The below results are given by Matlab simulation based on figure (3.10) with aid of paragraph 3.6.1 scenario.

4.2.1 Position estimation for four anchor nodes.

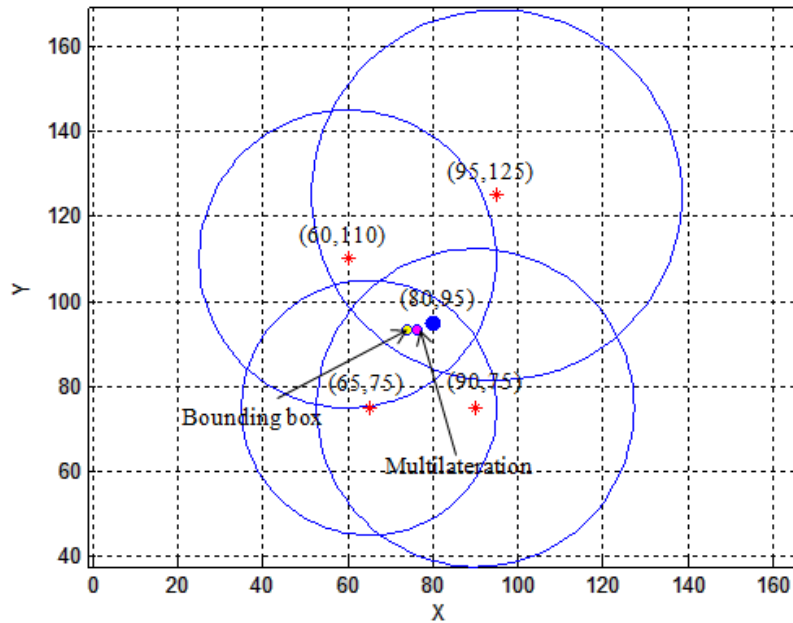


Figure 4.5: Estimated unknown node position with aid of four anchor nodes.

In this case the MATLAB program deploys the nodes randomly with a the limits of the communication range (100m) and then it estimates the position using multilateration and bounding box positioning methods, the results are compared in table 4.4 below.

Table 4.4: Multilateration and bounding box results for four anchor nodes

	Multilateration	Bounding box
Maximum Coordinates (x_{max}, y_{max})	-	(95, 105)
Minimum coordinates (x_{min}, y_{min})	-	(52.64, 81.46)
Unknown node position (x_u, y_u)	(76.93, 93.39)	(73.82, 93.23)
Position Error (PE)	3.94 m	6.43 m

4.2.2 Number of anchor nodes vs. versa PE.

Table 4.5 below gives a brief comparing for MAE between multilateration and bounding box for three and more anchor nodes, results shows that the decreasing of anchor nodes gives increasing of MAE in multilateration positing method and also MAE decreasing in bounding box positioning estimation method.

Table 4.5: position estimation methods MAE at 100m communication range

Number of anchor nodes	Mean Absolute Error of position estimation Multilateration (MAE) (m)	Mean Absolute Error of position estimation Bounding box (MAE) (m)
3	5.15	25.3
4	4.08	26.7
5	3.8	27.2
6	3.2	29.2
7	2.3	31.9

4.3 Distance vector hop algorithm results.

The below results are given by Matlab simulation based on figure (3.11) with aid of paragraph 3.6.2 scenario.

4.3.1 Bounding box method

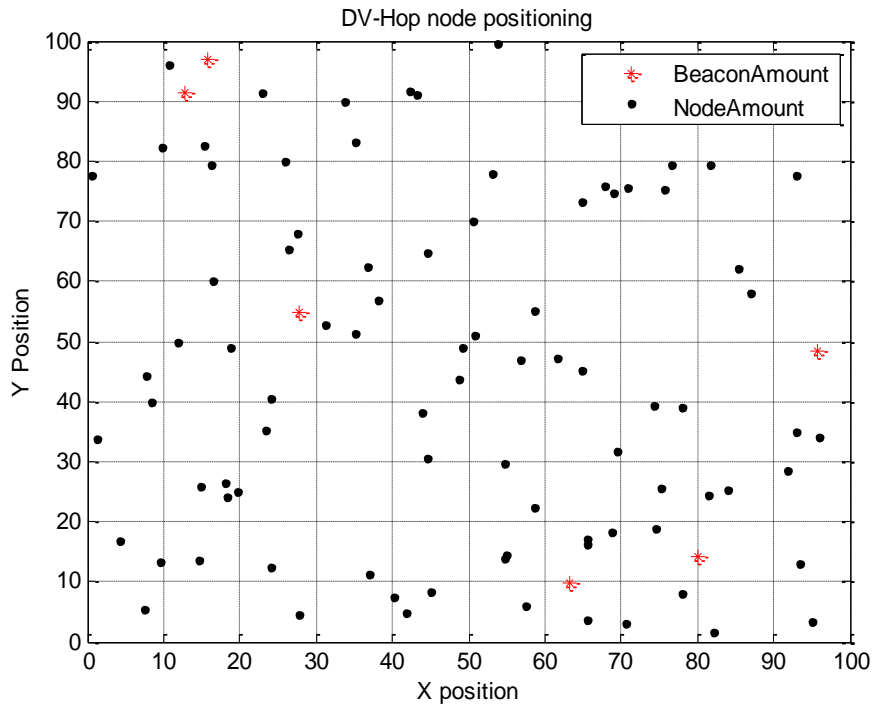


Figure 4.6: DV-Hop algorithm nodes distribution for bounding box method

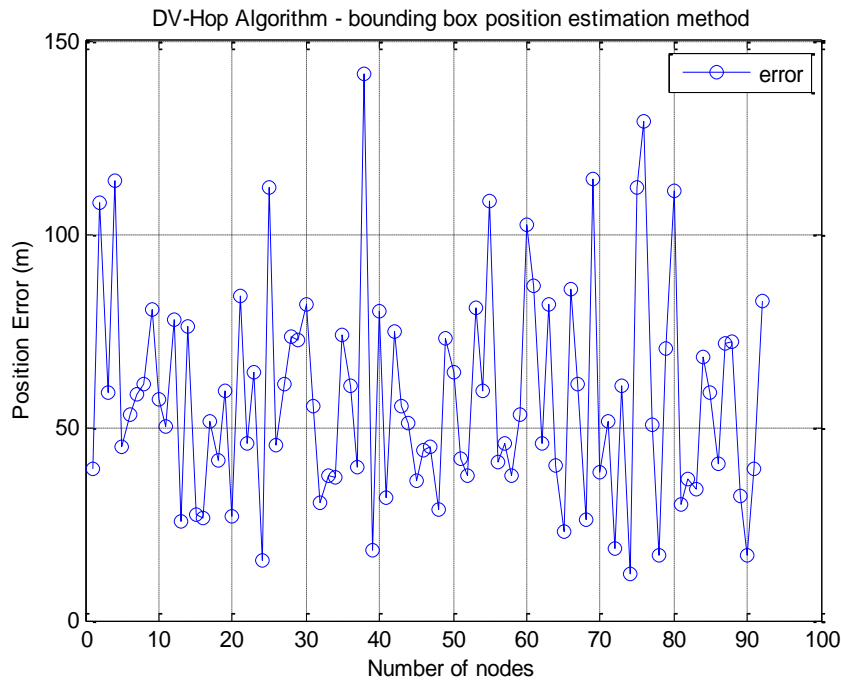


Figure 4.7: DV-Hop algorithm Position error using bounding box method
Bounding box mean absolute error metric (MAE) = **57.6268** m

4.3.2 Multilateration method.

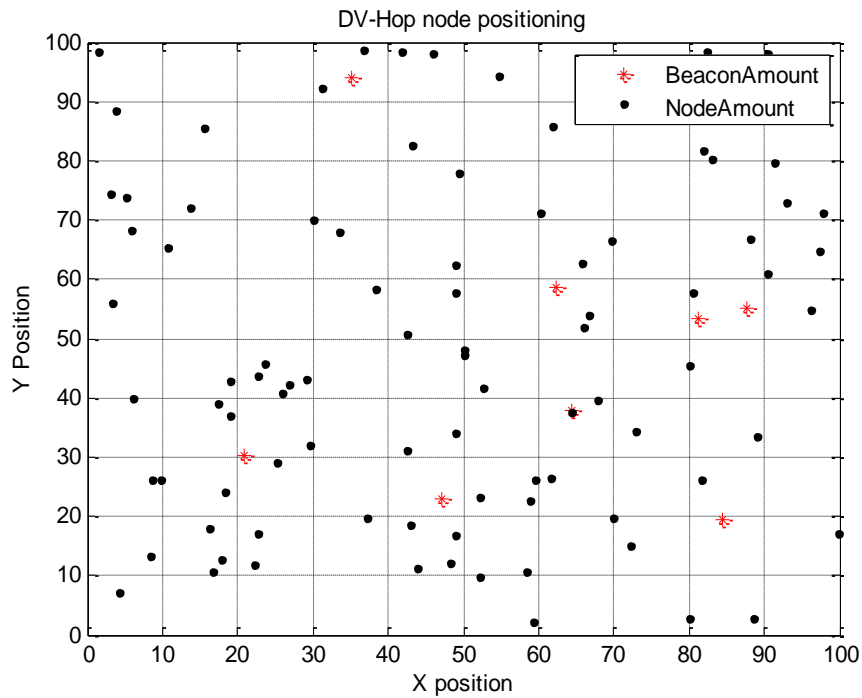


Figure 4.8: DV-Hop algorithm nodes distribution for multilateration method

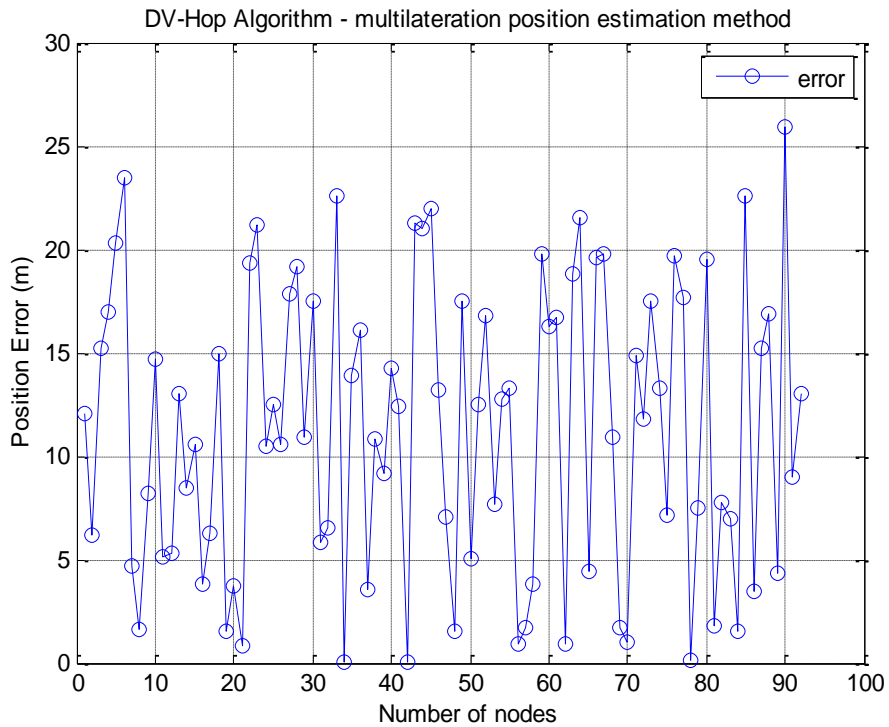


Figure 4.9: DV-Hop algorithm Position error using multilateration method

Multilateration mean absolute error metric (MAE) = **15.6096** m

4.4 Results discussion.

4.4.1 Position estimation.

To estimate its position using trilateration, unknown node needs to know the positions of the three anchor nodes and its correct distance from each of these anchor nodes. Therefore there is no error in estimation receiver position if the measurement distances are correct ($DME=0$) when using trilateration method, but this case is ideal case cannot be found in reality. The results showed that this method is very sensitive to distance measurement error (DME).

Bounding box is extremely simple but tends to localize anchor nodes in the center of the box area and this lead to error in estimating the position of unknown node even if measured correct distance values ($DME=0$).

Results show that bounding box method is insensitive to distance measurement error (DME) and more affected by anchor nodes placement.

The analyzed results have shown that the performance of position estimation methods are affected by several factors, such as anchor nodes placement, number of anchor nodes and estimated distance errors.

The results show that if the anchor nodes cannot be placed uniformly while distributed across the network; the accuracy of the unknown nodes positions at the edges is rather poor. Iteration method, on the other hand, performs much better.

Unknown nodes at the edges are less accurately than interior nodes, but the magnitude and variance in the errors is smaller than it for bounding box. Also from the results in previous tables it can deduced that the error in estimating position error (PE) is directly proportional with the distance measurement error (DME) in each both of trilateration and multilateration methods, while is constant in the bounding box method.

4.4.2 Distance vector hop algorithm.

The results shows that the mean absolute error of DV-hop increase while using bounding box positioning estimation method as discussed in 4.4.1; the accuracy of the unknown nodes positions at the edges is rather poor.

Chapter Five

Conclusion and Future works

5.1 Conclusion.

According to the explained results, it is deduced that when the DME is less than 3 meters in communication range of 100 meters; is better to use the trilateration method because the position error is less than the position error in bounding box method.

If the amount of DME is more than 3 meters it is preferred to use the bounding box method because it is less sensitive to DME, which improve the performance of localization system by enhancing the estimation the accuracy of receiver position. Multilateration position estimation based used in DV-Hop algorithm simulation.

DV-Hop algorithm is very simple and it has convenient operation, high efficiency and low energy consumption. It uses the average hop distance to calculate the actual distance, which has a low demand for hardware devices. The disadvantage is that using hop distance instead of straight line distance causes some errors.

What's more, considering the factors such as network latency, the average hop distance in DV-Hop algorithm is difficult to guarantee that it is obtained from the nearest anchor node. Therefore, the localization accuracy in DV-Hop algorithm needs further improved. In term of overhead, the DV-hop based algorithms have higher network overhead.

Node mobility can have a bigger influence on the accuracy of DV-hop algorithms because DV-hop based algorithms need longer localization period to support the broadcasts through the network.

MATLAB neglects the possible problems of a real wireless network context such as frame collision and node synchronization.

5.2 Recommendation and Future works.

1. Evaluate the performance of DV-hop algorithm by proposing modifications to the localization algorithm by using a correction factors to calculate the average hop distance for the unknown node.
2. Implementing and improving new localization algorithms.
3. Implementing some methods for mobile system base stations overhead as low as possible and low enough to make it viable.
4. Investigate methods to minimize the random delay and improve the consumed throughput per unit energy overhead if random access MAC is used in WSNs.
5. Design new data payload formats and a new access method to improve the performance of non-slotted CSMA/CA in the IEEE 802.15.4 wireless network.
6. Taking the radio variation such as environment, antenna of node and battery of node into consideration and to improve the localization algorithms.
7. Implementation thesis work into prototypes. Though the realization into prototypes which can finally obtain the performance of algorithms and protocols in real environment.
8. Apply RSSI position estimation method in obtaining the location of sensors obtained to analysis the electric field distribution under the High-Voltage Direct Current (HVDC) transmission lines.

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Appendix

IEEE 802.15.4 Technology

IEEE 802.15.4 wireless technology is a short-range communication system intended to provide applications with relaxed throughput and latency requirements in WPAN.

The key features of 802.15.4 wireless technology are low complexity, low cost, low power consumption, low data rate transmissions, to be supported by cheap either fixed or moving devices.

The main field of application of this technology is the implementation of WSNs. The IEEE 802.15.4 Working Group focuses on the standardization of the bottom two layers of ISO/OSI protocol stack. There are two options for the upper layers definition: Zigbee protocols, specified by the industrial consortia ZigBee Alliance and 6LowPAN.

IEEE 802.15.4 Physical Layer.

The 802.15.4 core system consists of a radio frequency (RF) transceiver and the protocol stack, depicted in Figure 1.

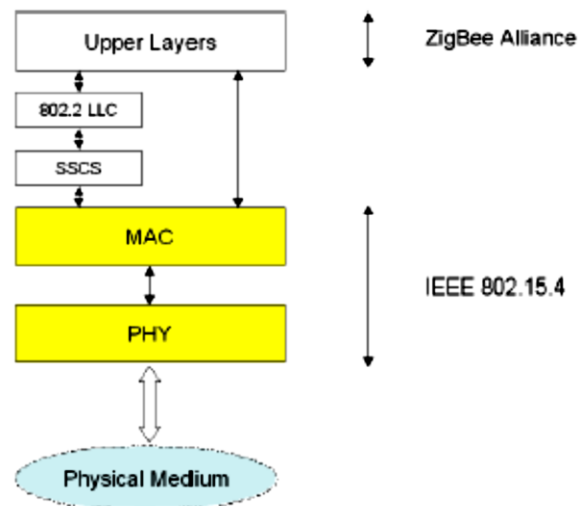


Figure 1 ZigBee protocol stack.

The 802.15.4 physical layer operates in three different unlicensed bands (and with different modalities) according to the geographical area where the system is deployed. However, spread spectrum techniques are wherever mandatory to reduce the interference level in shared unlicensed bands. IEEE 802.15.4 specifies a total of 27 half-duplex channels across the three frequency bands and is organized as follows:

- 1. The 868 [MHz] band:** only a single channel with data rate 20 [kbps] is available; -92 [dBm] RF sensitivity required and ideal transmission range approximately equal to 1 [km].
- 2. The 915 [MHz] band:** ten channels with rate 40 [kbps] are available; the receiver sensitivity and the ideal transmission range are the same of the previous case.
- 3. The 2.4 [GHz] ISM band:** sixteen channels with data rate 250 [kbps] available; minimum -85 [dBm] RF sensitivity required and ideal transmission range equal to 220 [m].

The ideal transmission range is computed considering that, although any legally acceptable power is permitted, IEEE 802.15.4 compliant devices should be capable of transmitting at -3 [dBm].

According to the energy efficiency issue, low rate and low duty cycle are provided. IEEE 802.15.4 compliant devices are active only during a short time and the standard allows some devices to operate with both the transmitter and the receiver inactive for over 99% of time.

IEEE 802.15.4 MAC Layer:

IEEE 802.15.4 uses a protocol based on the CSMA/CA algorithm, which requires listening to the channel before transmitting to reduce the probability of collisions with other ongoing transmissions.

IEEE 802.15.4 defines two different operational modes, namely the anchor-enabled and the non-anchor enabled, which correspond to two different channel access mechanisms.

In non-anchor enabled mode nodes use an unslotted CSMA/CA protocol to access the channel and transmit their packets. The algorithm is implemented using units of time called backoff periods.

First, each node will delay any activities for a random number of backoff periods. After this delay, channel sensing is performed for one unit of time: if the channel is found free the node immediately starts the transmission; if, instead, the channel is busy the node enters again in the backoff state. There exists a maximum number of time the node can try to access the channel (i.e., to sense the channel).

When this maximum is reached, the algorithm ends and the transmission cannot occur. In the anchor enabled mode, instead, the access to the channel is managed through a super frame, starting with a packet, called anchor, transmitted by WPAN coordinator.

The super frame may contain an inactive part, allowing nodes to go in sleeping mode, whereas the active part is divided into two parts: the Contention Access Period (CAP) and the Contention Free Period (CFP), composed of Guaranteed Time Slots (GTSs), that can be allocated by the sink to specific nodes (see Figure 2). The use of GTSs is optional.

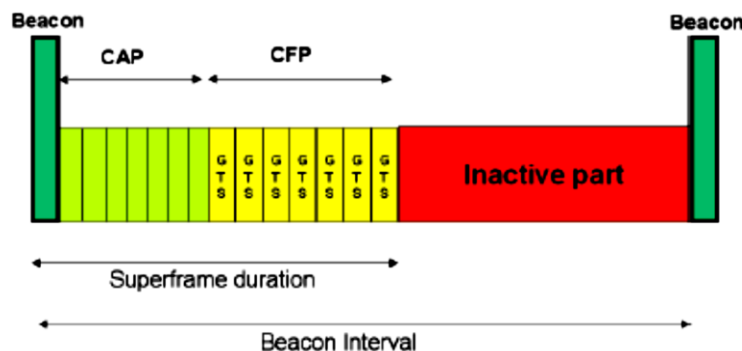


Figure 2 Super frame structure.

The duration of the active part and of the whole super frame, depend on the value of two integer parameters ranging from 0 to 14, that are, respectively, the super frame order, denoted as SO, and the anchor order, denoted as BO.

BO defines the interval of time between two successive anchors, namely the anchor interval, denoted as BI.

The duration of the active part of the super frame, containing CAP and CFP, namely the super frame duration, denoted as SD.

For what concerns the CSMA/CA algorithm used in the CAP portion of the super frame the only difference with the non-anchor enabled mode is that nodes have to find the channel free for two subsequent backoff periods before transmitting the packet.

The other difference with the non-anchor enabled case is that backoff period boundaries of every node in the WPAN must be aligned with the super frame slot boundaries of the coordinator; therefore, the beginning of the first backoff period of each node is aligned with the beginning of the anchor transmission. Moreover, all transmissions may start on the boundary of a backoff period.

IEEE 802.15.4 Network Topologies and Operational Modes.

To overcome the limited transmission range, multi-hop self-organizing network topologies are required. These can be realized taking into account that IEEE 802.15.4 defines two types of devices:

1. The Full Function Device (FFD).
2. The Reduced Function Device (RFD).

FFD contains the complete set of MAC services and can operate as either a PAN coordinator or as a simple network device.

RFD contains a reduced set of MAC services and can operate only as a network device. An example of IEEE 802.15.4 compliant network topologies is shown in Figure 3. Two basic topologies are allowed, but not completely described by the standard since definition of higher layers functionalities are out of the scope of 802.15.4.

- i. The star topology, formed around an FFD acting as a PAN coordinator, which is the only node allowed to form links with more than one device.
- ii. The peer-to-peer topology, where each device is able to form multiple direct links to other devices so that redundant paths are available.

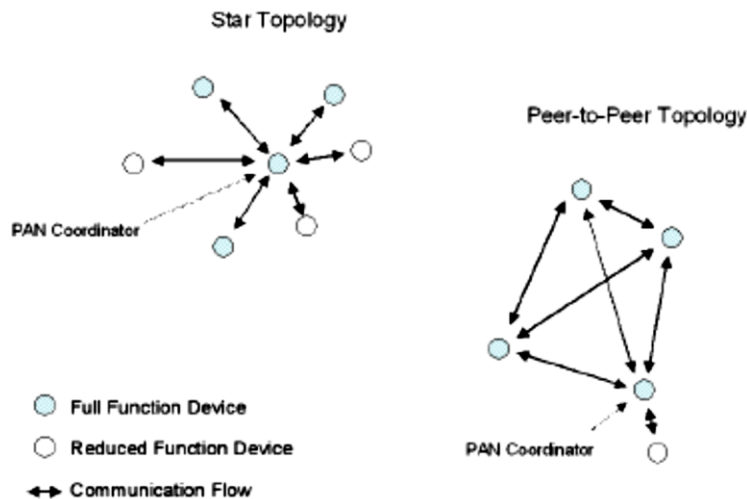


Figure 3 IEEE 802.15.4-compliant network topologies

Star topology is preferable in case coverage area is small and low latency is required by the application. In this topology, communication is controlled by the PAN coordinator that acts as network master, sending packets, named anchors for synchronization and managing device association.

Network devices are allowed to communicate only with the PAN coordinator and any FFD may establish its own network by becoming a PAN coordinator according to a predefined policy.

A network device that wishes to join a star network listens for an anchor message, and after receiving it, the network device can send an association request back to the PAN coordinator, which either allows or denies the association.

Star networks also support a non-anchor enabled mode. In this case, anchors are used for association purpose only, whereas synchronization is achieved by polling the PAN coordinator for data on a periodic basis. Star networks operate independently from their neighboring networks.

Peer-to-peer topology is preferable in case a large area should be covered and latency is not a critical issue. This topology allows the formation of more complex networks and permits any FFD to communicate with any other FFD behind its transmission range via multi hop.

Each device in a peer-to-peer structure needs to proactively search for other network devices. Once a device is found, the two devices can exchange parameters to recognize the type of services and features each supports. However, the introduction of multi hop requires additional device memory for routing tables.

IEEE 802.15.4 can also support other network topologies, such as cluster, mesh, and tree. These last network topology options are not part of the IEEE 802.15.4 standard, but are described in the ZigBee Alliance specifications.

All devices belonging to a particular network, regardless of the type of topology, use their unique IEEE 64-bit addresses and a short 16-bit address is allocated by the PAN coordinator to uniquely identify the network.

The IEEE 802.15.4 Topology Formation Procedure.

The IEEE 802.15.4 defined a mechanism to support a PAN coordinator in channel selection when starting a new PAN, and a procedure, called association procedure, which allows other devices to join the PAN.

A PAN coordinator wishing to establish a new PAN needs to find a channel free from the interference that would render the channel unsuitable (e.g., in a multi-sink network, a channel may be already occupied by other PANs).

The channel selection is performed by the PAN coordinator through the Energy Detection (ED) scan which returns the measure of the peak energy in each channel. It must be noticed that the standard only provides the ED mechanism, and it does not specify the channel-selection logic.

The operations accomplished by a device to discover an existing PAN and to join it can be summarized as follows:

- i.** search for available PANs.
- ii.** select the PAN to join.
- iii.** start the association procedure with the PAN coordinator or with another FFD device, which has already joined the PAN.

The discovery of available PANs is performed by scanning anchor frames broadcasted by the coordinators.

Two different types of scan that can be used in the association phase are proposed:

- 1. Passive scan:** in anchor-enabled networks, the associated devices periodically transmit anchor frames, hence the information on the available PAN can be derived by eavesdropping the wireless channels.
- 2. Active scan:** in non-anchor-enabled networks, the anchor frames are not periodically transmitted but shall be explicitly requested by the device by means of anchor request command frame.

After the scan of the channels, a list of available PANs is used by the device to choose the network to try to connect with. In the standard, no specific procedure to select a PAN is provided and so, this selection among potential parents is open for different implementations. Hence, the device sends an association request frame to the coordinator device by means of which the selected network was discovered. The association phase ends with a successful association response command frame to the requesting device.

This procedure basically results in a set of MAC association relationships between devices, named in the following parent-child relationship. [20]

