ANCHOR NODES PLACEMENT FOR EFFECTIVE PASSIVE LOCALIZATION

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Wireless sensor networks are composed of sensor nodes, which can monitor an environment and observe events of interest. These networks are applied in various fields including but not limited to environmental, industrial and habitat monitoring.

In many applications, the exact location of the sensor nodes is unknown after deployment. Localization is a process used to find sensor node's positional coordinates, which is vital information. The localization is generally assisted by anchor nodes that are also sensor nodes but with known locations. Anchor nodes generally are expensive and need to be optimally placed for effective localization.

Passive localization is one of the localization techniques where the sensor nodes silently listen to the global events like thunder sounds, seismic waves, lighting, etc. According to previous studies, the ideal location to place anchor nodes was on the perimeter of the sensor network. This may not be the case in passive localization, since the function of anchor nodes here is different than the anchor nodes used in other localization systems. I do extensive studies on positioning anchor nodes for effective localization. Several simulations are run in dense and sparse networks for proper positioning of anchor nodes. I show that, for effective passive localization, the optimal placement of the anchor nodes is at the center of the network in such a way that no three anchor nodes share linearity. The more the non-linearity, the better the localization. The localization for our network design proves better when I place anchor nodes at right angles.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

Wireless sensor networks (WSN) are made of spatially distributed sensor nodes which are normally tiny in size that can be used to monitor environmental or physical conditions like pressure, temperature, audio, video, motion, etc. These sensor nodes typically have a low-power processor, a sensor board, a memory, a transceiver and a power source of size similar to AA batteries [1].

These nodes may be deployed in places where there are no power sources. Wiring for power supply may not be just expensive but also hard to connect. They are generally equipped with small memory to store or retrieve data. The transceivers are capable of transmitting and receiving radio signals to several meters of distance. Due to this limited transmission range, a sensor node may use its neighboring nodes to route the data to its end user. This gives rise to different routing algorithms for WSN.

WSN generally consist of a base station, which can communicate wirelessly with the sensor nodes (Figure 1.1).

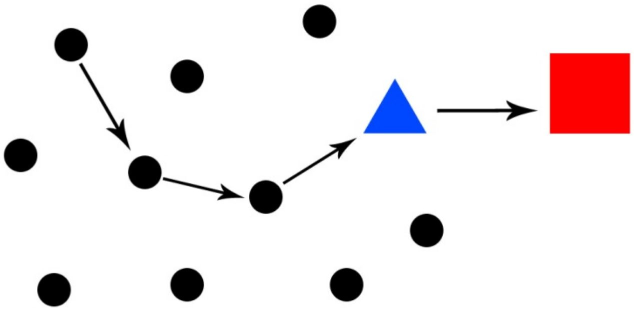

Figure 1.1. A typical Wireless sensor network. Circles (black) represent sensor nodes and triangle (blue) represents a base station. The information is routed through nodes and finally the end user represented by a square (red) receives the information through the base station.

These sensor nodes collect data, compress and transmit to the base station [2]. These sensor nodes may transmit data to base station either directly or indirectly through other sensor nodes present in the network using routing algorithms.The nodes may either store and transmit raw data to its base station or process and transmit processed data to its base station.

As one can fathom, in the latter case, the node consumes more power. But it may be used in situations to avoid transmission time (hence more battery life). The nodes may transmit the raw data in applications where continuous data processing is involved. In mobile networks involving continuous sensing and positional tracking, the data is processed at the sensor node. In such networks, the sensor node cannot afford to wait until the base station processes and transmits the information back.

Although WSN have various applications, there are certain limitations. They are limited in resources such as short battery lifetime, low processing power, limited memory, etc., to survive in an adverse environment. Since, WSN are designed for unattended operations, its resources have to be effectively managed and utilized to extend the lifetime of the WSN.

1.1. Architecture

A typical sensor node contains four blocks: sensing unit, processing unit, communication unit and a power source unit (Figure 1.2).

The sensing unit usually consists of two parts: a sensor and an analog-to-digital converter (ADC). The sensor of interest produces analog signals that are converted to digital signals by ADC and then forwarded to the processing unit.

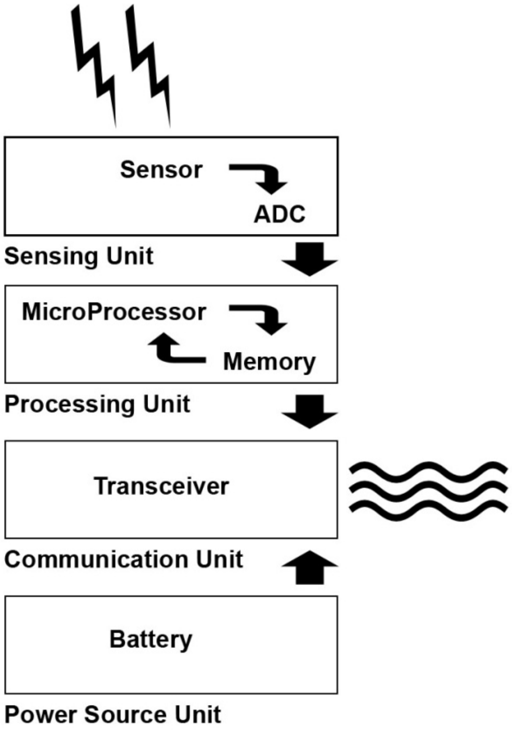

Figure 1.2. Architecture of a sensor node containing four different units.

The processing unit usually has memory, applications and a microprocessor, which together process the digital data obtained from ADC. The microprocessor then decides whether or not to transmit the data. The transmission and reception are done at the communication unit.

The communication unit consists of a transceiver, which is capable of both transmitting and receiving information. Transmission is the only process that consumes most of the battery power in a sensor node. The greater the distance between a transmitter and a receiver, the larger is the energy utilized. There are several methods to minimize power consumption due to transmission.

The transmission and reception can be of radio frequency (RF) or infrared (IR) or Bluetooth. Bluetooth or IR may be used for short-range communications. But IR cannot be used for out of sight targets. Therefore, in general RF communication is preferred.

The power unit, which is one of the most important components of a sensor node, consists of a battery for power source. These may be of different sizes from small button sized cells to AA sized batteries for longer lifetime. These batteries are of one time use and may not be replaced after deployment. The processing unit is again responsible for optimal power consumption in a sensor node.

A sensor node contains an operating system that has several duties. For example, it has to manage power consumption, control communication with other nodes, schedule tasks and run applications. TinyOS is a common operating system found in sensor nodes. It is a power efficient, event-driven and component based operating system which is an open source written in a language similar to C known as NesC-Language [3]. TinyOS is also popular for running networking applications within few kilobytes of memory usage.

The sensor found in sensing unit may be of different types based on the application. Some of the well known sensors are used to sense seismic, visual, infrared, radar, acoustic and thermal signals. These sensors can be used in different conditions. For example, it can be used to monitor temperature, pressure, humidity, target movement, noise, lightning, physical stress, speed and direction of moving target [4].

Apart from these, the sensor nodes may have additional components like location systems (Global Positioning System), power generator, etc. Some outdoor sensor networks use solar cells for power source.

1.2. Applications

There are several applications for WSN, which involve monitoring and tracking.

Developments in sensor networks were motivated from battlefield applications in the military. Now, they are used in many industrial and civilian areas.

WSN has a wide range of applications in the fields such as military, industrial, domestic, and environmental areas. WSN are used in the military for communication, surveillance, reconnaissance, computing and target tracking. It can also be used for monitoring friendly and opposing forces. For example, it can be used to assess damage caused in a battle, to detect chemical, biological or nuclear attack. They can be used for battlefield surveillance by sensing acoustic and magnetic signals produced by target objects such as vehicles and troop movements [5]. WSN is a promising technology in the military due to its characteristics like rapid deployment, error diagnosis and self-organization. During war, they reduce casualties providing critical reaction time for the troops to react. WSN can also be used for safety purposes like reconnaissance of nuclear radiation without a soldier getting exposed to it.

There are ongoing research studies to identify a shooter’s location using sensor networks [6]. Here, the sensor nodes measure the muzzle blast and shock waves created by the moving bullet to identify the exact location of the shooter.

WSN are used in environmental applications for tracking animals, birds and environmental conditions that affect crops. It can be used to monitor soil conditions for irrigation, fertilization and harvesting. WSN are used to detect forest fires, floods [7] and volcanic activity [8]. To detect a forest fire, many sensor nodes are deployed in a forest at high density. These sensor nodes can detect the exact location of the origin of the fire. This helps fire fighters to prevent fire from spreading uncontrollably. WSN can be used for monitoring the air for pollution by attaching gas sensors to mobile vehicles or fixed locations on the street [9]. WSN can also used to monitor permafrost to study the slope stability to avoid natural hazards [10].

In the health industry, sensor networks can be used to monitor doctors, patients and drug administrators [11]. They can be used in hospitals [12] to monitor physiological signals like blood pressure, blood glucose level, body temperature, pulse oxygen saturation, electrocardiogram, etc. They can also be used to monitor internal infection processes of a human body. Attaching sensor nodes to medications, could avoid administration of wrong medications to patients with specific allergies [13].

For domestic purposes, WSN can be used to create smart home environment where devices like vacuum cleaners, ovens, disk players and refrigerators can be connected with sensor nodes. These devices can thus interact with each other and communicate with an end user locally or remotely through the internet. One such application is Smart Kindergarten which can be used to solve developmental problems of young children where they learn by interacting with objects like toys attached with sensors, in their environment [14].

WSN can be used in industry to monitor material fatigue, product quality, wind tunnels, guidance for robots and machine diagnosis to name a few. WSNs are also used in the car industry for automotive testing [15]. WSN can also be used for real time monitoring of nuclear power plants for radiation and faults [16].

All of these applications to be feasible, the system might require the proper reporting of their positional coordinates to obtain a meaningful outcome. This can be achieved by localization of WSN.

1.3. Importance of Localization

During deployment of sensor nodes, due to situational or environmental constraints it is difficult to carefully place these sensor nodes at known locations. Using the global positioning system (GPS) may be a good choice, which can provide accuracy of up to few centimeters of distance, depending on available resources [17]. But, it is not feasible to equip each node with a GPS. They are expensive and they do not work in many places like indoor environment and places with meager satellite coverage. Sometimes efficient data routing may also rely on sensor's location [18]. Therefore, we need a localization algorithm that can pinpoint the sensor nodes on a reference or global coordinate system.

There are several localization techniques like received signal strength (RSS), time of arrival (TOA) and angle of arrival (AOA). The details of each algorithm are covered in Chapter 2. Every technique carries its own advantages and disadvantages depending on the application of the WSN.

In this research, I have used passive localization, which uses the time differences between global events to localize the sensor nodes [19]. The main advantage of using passive localization is, as the name implies, the nodes have to just listen or measure the signal strength for localization. The signals could be global events occurring around the sensor bed like thunder, wind, tremor, etc. This localization technique like other techniques also requires anchor nodes. Anchor nodes are sensor nodes with known locations. This can be achieved by either equipping them with GPS or by carefully deploying it at known locations.

Although passive localization uses anchor nodes, its function is slightly different from other localization techniques. Unlike anchor nodes in other techniques, anchor nodes in passive localization do not transmit signals for localization. They just listen for global events for localization.

It is well known that increasing the number of anchor nodes gives rise to better localization. But increasing the number of anchor nodes may not be a feasible solution due to extra hardware requirements that may be more expensive.

Some researchers have said that it is better to place anchors uniformly on the perimeter of the network [18, 20]. This may not be the case in passive localization, since the signals are transmitted from global events which may be far away from the senor bed. Moreover, placing anchors with known locations and sensor nodes with unknown locations on the same perimeter makes less sense. It would be easier and less expensive to deploy anchor nodes within the network. I have done several simulations to study optimal placement of anchor nodes for effective localization. The purpose of optimal positions of anchor nodes are: (1) to reduce localization error, (2) to avoid deployment costs. Deployment cost of the anchor nodes need to be considered since we need to know its geographical coordinates.

This thesis is structured as follows:

Chapter 2 discusses different localization systems. Some of the common localization techniques are discussed in detail. These techniques are then compared with each other.

Chapter 3 discusses the details of passive localization and the importance of positioning of anchor nodes for localization. Different parameters and strategies to consider while deploying anchor nodes are also discussed.

Chapter 4 presents the results of various simulations carried to study the effects of anchor node's position on localization errors. I present various results of simulations that were carried on sparse as well as dense WSN.

Finally, I conclude our study on positioning anchor nodes for effective passive localization in Chapter 5. I also discuss possible future directions to extend our research.

CHAPTER 2

LOCALIZATION

Many applications need positional information of sensor nodes and these positions can be acquired by using localization algorithms. There are two main approaches in localization: distributed and centralized system [21].

In a distributed system, individual nodes determine the location information by cooperating with other nodes whereas in a centralized system, a central server determines the location.

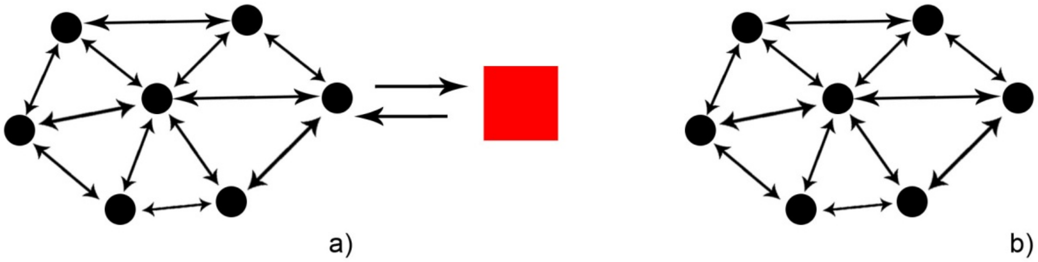

Figure 2.1. Localization systems in Wireless sensor networks (WSN). (a) Centralized system. Nodes report their ranging estimates to a base station (square), which computes their location (b) Distributed system. Nodes co-operate with each other to calculate their location.

In centralized system, individual nodes transmit all the localization information to a central server, which then computes the location of each of its nodes. The advantage of this approach is that all information is given to the central server. Therefore, the system is not limited by specific algorithm to use. This also gives rise to more accurate results, as the system does not have any limit to process the data. The main disadvantages of this system are traffic congestion and computational complexities.

On the other hand, in a distributed system, the localization is distributed across the network. The node attempts to localize itself and helps in localizing other nodes.

This process is usually iterative. The algorithms used are generally energy efficient and self-organizing.

The two main challenges for localization can be divided into network and channel parameter [21]. Considering network parameters, the localization is affected by the size of nodes, anchors, topology and network's connectivity. Anchors are also nodes with known location. They may be either deployed at known location or may be equipped with GPS for location. A network with dense nodes gives rise to better localization than a network with sparse nodes. This may be due to poorly connected nodes in sparse networks. It may be better to have dense nodes, but with increasing number of nodes, the error propagation also increases.

Considering channel parameters, the localization techniques are also affected. Common localization techniques depend on Radio Frequency (RF) ranging. Some of the examples are Time of Arrival (TOA), Received Signal Strength (RSS) and Angle of Arrival (AOA). TOA technique is more accurate than RSS technique but the latter is more practical than TOA. The performance of these techniques varies when deployed in outdoor environments and indoor environments. This is due to the uncertainty of the RF propagation, which may cause severe localization errors. To avoid these errors, the channel needs to be investigated for a compatible localization algorithm.

The localization system can be separated into three functional components [22]: Distance/Angle estimation, position computation and localization algorithm (Figure 2.2).

The distance/angle estimation component estimates distance or angle between two nodes. This information may be used by other components.

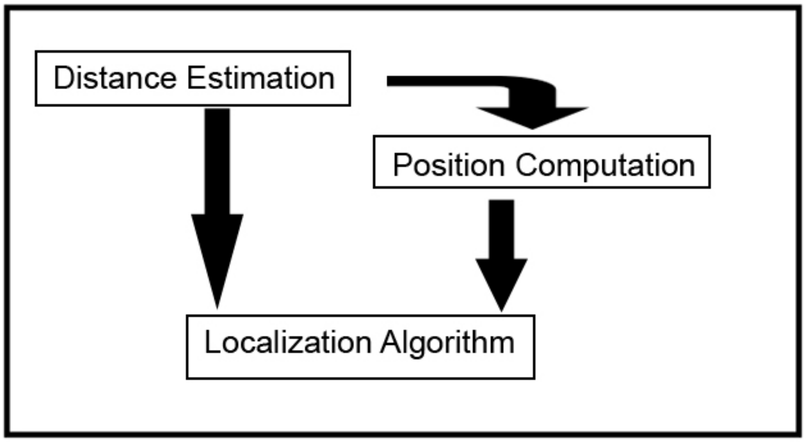

Figure 2.2. Different components of localization systems. Distance estimation, position computation and Localization algorithm.

The position computation component uses the distance or angle information of anchor nodes to estimate node's position. Localization algorithm component is the heart of localization system. This component determines the manipulation of the available information to let other nodes to estimate their position. Since every node in a sensor network is equipped with a radio for communication, this unit can be used for range estimation techniques.

2.1. Received Signal Strength

RSS can be used to deduce the distance between a transmitting node and a receiving node. Theoretically, this signal strength follows the inverse square law, where the signal strength is inversely proportional to the square of the distance between the transmitter and the receiver.

Practically, this technique results in error in the order of several meters [23]. This may to due to non-uniform distribution of radio signals in space. Signal propagation on different mediums such as air and water differs.

2.2. Radio Hop Count

In this technique, the radio is again used for localization. It functions based on the the fact that if two nodes on a network can communicate, then the distance between them is at the most R, which is the maximum range of the radio irrespective of their signal strengths (Figure 2.3) .

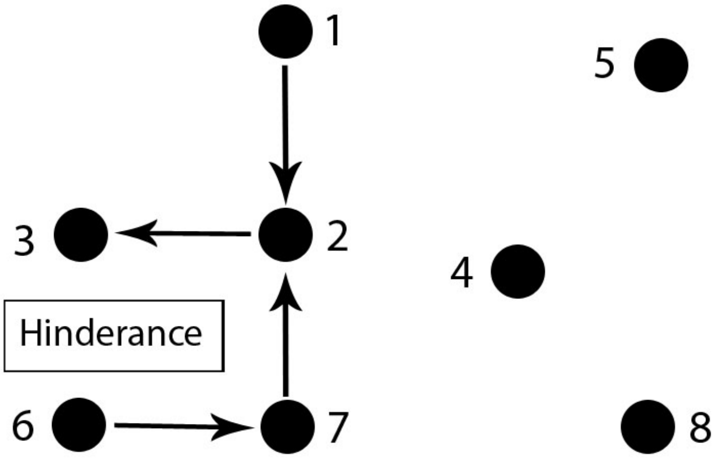

Figure 2.3. Hop count (h) in WSN. For example: h_{13} = 2, h_{63}=3.

If the hop count between nodes n_i and n_j is h_{ij}, then the physical distance d_{ij} is less than $R*h_{ij}$. However a better estimate of d_{hop} (distance covered by one radio hop) can be found using n_{local} (the expected number of neighbors per node) like [24]:

$$d_{hop} = R(1 + e^{-n_{local}} - \int_{-1}^{1} e^{-\frac{n_{local}}{\pi}(\arccos t - t\sqrt{1-t^2})} dt) \qquad (2.1)$$

Therefore, $d_{ij} \sim h_{ij}*d_{hop}$.

Since it is a multiple of d_{hop}, small inaccuracy might lead to large d_{ij} error.

One main problem with this technique as we can see in Figure 2.3, is that the hop count between node 6 and node 3 is 3 while it has to be 1. This is due to the physical hindrance between node 3 and node 6 blocking the RF signal across.

2.3. Time of Arrival

In this technique, the sensor nodes are equipped with a speaker and a microphone. A radio signal is first transmitted by the transmitter and then after a fixed interval of time t_d, fixed patterns of audio signals are transmitted.

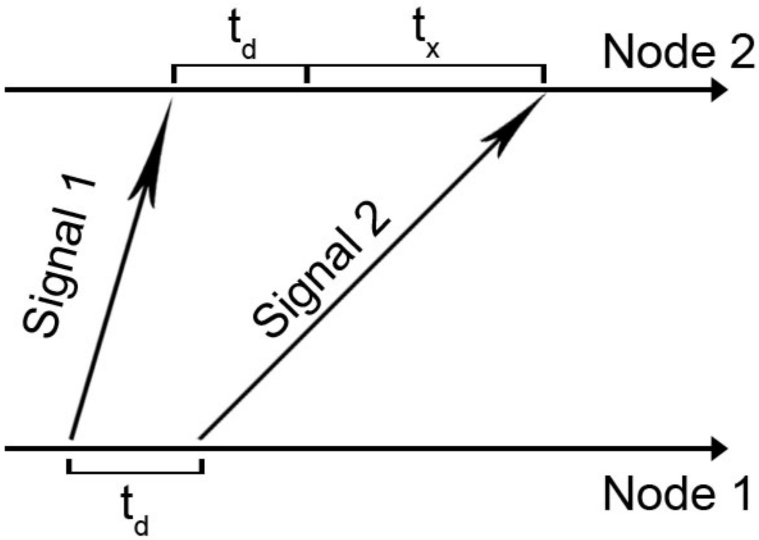

Figure 2.4. Time of Arrival. Node 1 transmits signal 1 (radio) followed by signal 2 (sound) to Node 2. These could be of different types. The time difference of arrival at Node2 can be used to calculate the distance between them.

The receiving node, records the time intervals at which radio wave (t_{radio}) and audio signal (t_{sound}) were received. Hence, the distance d between a transmitting and a receiving node can be calculated as follows:

$$d = (s_{radio} - s_{sound}) \times (t_{sound} - t_{radio} - t_d), \qquad (2.2)$$

where s_{radio} and s_{sound} are speed of radio and sound respectively.

This technique may not perform well in places prone to echoes. The nodes too require special calibrated hardware (speaker and microphone) for localization. The speed of audio waves may also vary with environmental conditions like humidity and temperature.

2.4. Angle of Arrival

This technique utilizes an array of receivers (radio or microphone), which receive and respond to the transmitted signal. By analyzing the phase or time difference received at different microphones, the direction of the transmitter can be determined by measuring the angle of arrival. This method can be accurate up to a few degrees of angle, but it is more expensive and bulky.

TOA seems to be more accurate compared to RSS techniques. However, both of them are vulnerable to occlusions. AOA technique involves more expensive and bulkier hardware than TOA techniques. Moreover, it is not practical to accommodate spatially separated microphones when the size of a sensor shrinks.

CHAPTER 3

ANCHOR NODE PLACEMENT

3.1. Passive Localization

Passive localization technique uses time differences of global events for localization (Figure 3.1). Some examples of such events are thunder sound, seismic data, moving clouds, lightning, etc. Since, the sensor nodes just sense the events and do not transmit while localization, it is known as passive localization [19]. The time difference between each pairs of nodes is proportional to the distances from the plane normal to the global event propagation and the sensor nodes. These time differences are known as projected distances.

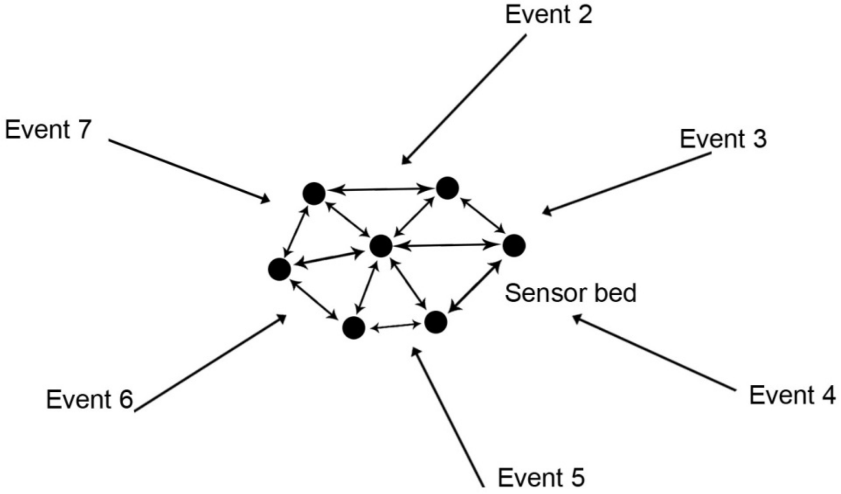

Figure 3.1. Passive localization. A sensor bed passively observes various global events surrounding it.

The global events are first detected by looking for similar raw signals at all sensor nodes. The similarity is checked by measuring the correlation between them. The received signals between each node are shifted by a time interval due to propagation delay. The time difference of arrival is then calculated between each pairs of nodes from detected events. These time shifts are nothing but the projected distances. The principal axes with largest variances are then computed from the set of projected distances. The position of the sensor nodes can then be obtained from linear combinations of the principal axes. The linear combination coefficients can be found using anchor nodes with known locations.

If we have *n* nodes and *m* sets of projected distances from each global event, then we can build a distance matrix *D* as follows:

$$D = \begin{bmatrix} u_{11} & u_{12} & . & . & u_{1m} \\ u_{21} & . & & & . \\ . & & . & & . \\ . & & & . & . \\ u_{n1} & . & . & . & u_{nm} \end{bmatrix}, \tag{3.1}$$

where u_{ij} = time at which signal arrives at node *i* from event *j*.

This matrix can be decomposed to three other matrices using singular value decomposition.

$$D = P.\Sigma.Q \tag{3.2}$$

The first two column vectors of matrix *P* are the most important principal axes of D. Let these vectors be $\mathbf{p_1}$ and $\mathbf{p_2}$. Then the node's position (x_i, y_i) can be obtained as follows:

$$\begin{aligned} x_i &= a_1.p_{1i} + b_1.p_{2i} + c_1, \\ y_i &= a_2.p_{1i} + b_2.p_{2i} + c_2, \end{aligned} \tag{3.3}$$

where $\mathbf{p_{ij}}$ is the j^{th} element of vector $\mathbf{p_i}$, a_1, a_2, b_1 and b_2 are the linear combination coefficients and c_1 and c_2 are the coefficient for the vector of ones.

Having six unknown variables, we need at least three anchor nodes to obtain all the nodes positions. Using more than three anchor nodes can improve the redundancy in computing the linear combination coefficients [19].

To calculate the nodes positions, let

$$\boldsymbol{s} = \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix}, \boldsymbol{t} = \begin{bmatrix} a_2 \\ b_2 \\ c_2 \end{bmatrix}, \boldsymbol{x} = \begin{bmatrix} x_1 \\ \cdot \\ \cdot \\ \cdot \\ x_k \end{bmatrix}, \boldsymbol{y} = \begin{bmatrix} y_1 \\ \cdot \\ \cdot \\ \cdot \\ y_k \end{bmatrix},$$

$$A = \begin{bmatrix} \mathbf{p_{11}} & \mathbf{p_{2k}} & 1 \\ . & . & . \\ . & . & . \\ . & . & . \\ \mathbf{p_{1k}} & \mathbf{p_{2k}} & 1 \end{bmatrix}, \text{ then} \tag{3.4}$$

$$\boldsymbol{s} = A^{+}.\boldsymbol{x}, \quad \boldsymbol{t} = A^{+}.\boldsymbol{y},$$

where *k* is the number of anchor nodes and A^+ is the pseudo inverse of matrix *A* [25,26]. After computing the linear coefficients, we can obtain the position of the each node by using Equation (3.3).

3.2. Anchor Node Placement

Conventionally several researchers have observed that anchor nodes should be uniformly spread around the perimeter of the sensor network [20]. As the deployment of anchor nodes are at unknown location and due to other conditions, it may not be possible to deploy anchor nodes uniformly at the perimeter of the sensor network.

No matter how the network is set up, the error associated with localization is inevitable. There may be various sources for this error. One of the serious sources is the unavailability of the anchor nodes. This may arise due to low deployment density or poor signal propagation due to factors like multipath effects, fading effects, dead zones and poor visibility [27].

The propagation of radio waves is unpredictable in practice making it sensitive to errors. The errors may also rise due to erratic measurements depending on hardware quality, time synchronization accuracy and ranging techniques used. The other source of error rises due to anchor node's position.

In the past, several articles have been published on localization techniques and very few articles address effective positioning of anchor nodes. This may be due to their focus on the localization techniques rather than parameters affecting localization.

I examined the effect of anchor node's positions on passive localization. Anchor node's placement and geometry plays a crucial role on localization.

In passive localization, unlike other localization techniques, the nodes are passive meaning they do not transmit and instead silently sense all the events happening around the network. Therefore, the function of the anchor nodes in passive localization is slightly different from other localization methods.

3.2.1. Density of the Anchor Nodes

Increasing the density of the anchor nodes may minimize localization error, but the cost of deployment and hardware may increase. The density of anchor nodes may still be increased to leverage redundancy.

3.2.2. Geometry of the Anchor Nodes

Geometry of the anchor nodes also affects localization. Deploying more than two anchor nodes in a line may not improve localization but may be used for fault tolerance.

I have done several simulations to study the positioning of anchor nodes for effective passive localization.

In the following chapter, I present the graphical user interface, which was developed using Matlab. I also present our simulation results of passive localization with different positions of anchor nodes.

CHAPTER 4

SIMULATION AND RESULTS

4.1. User Interface

An interactive graphical user interface (GUI) was developed in Matlab (Figure 4.0). The system can either randomly create nodes or let the user place the nodes manually. The global events are randomly generated across the network.

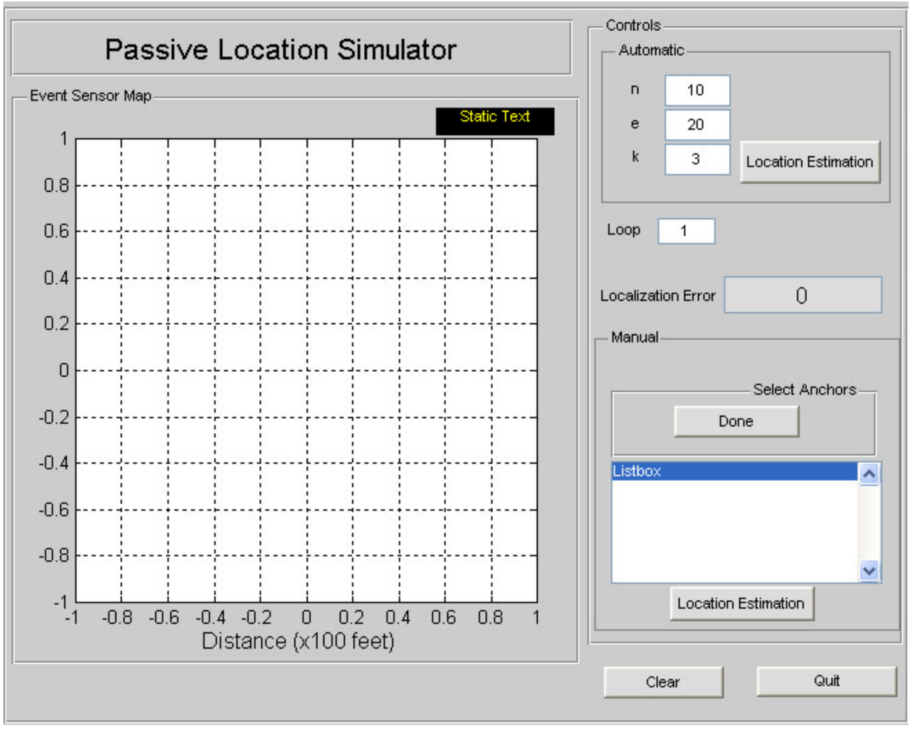
n 10
e 20
k 3
Loop 1
Localization Error 0

Figure 4.0. GUI for passive localization simulation developed using Matlab. Here *n* represents the number of sensor nodes, *e* represents the number of events and *k* represents the number of anchor nodes used.

About 20-30 global events were randomly created around the sensor network. Each event is assumed to create a signal which propagates at a constant speed. For simplification, the propagation velocity was considered to be unity. In the first part of our study, the positions of sensor nodes were randomly generated to study the dependence of the number of global events and the number of anchor nodes on localization. In the second part, the positions of sensor nodes and anchor nodes were fixed to study the effect of positioning of anchor nodes over localization.

4.2. Assumptions

For the sake of simplicity, I have made the following assumptions. I considered the propagation velocity of all global signals to be unity. I assumed the clocks within each node are time synchronized. I assumed that global events are distributed around the network. Signal processing steps were skipped since I am not working with real signals. I ignored redundancy to assume an ideal case. However, in the real world redundancy is considered to manage node failures. I assumed all the global event sources to be static. However, in actuality, there may be some mobile global events where the time shift between two nodes may not be proportional to the distance between them.

4.3. Localization Error

Every localization technique is associated with an error which is inevitable even with the best techniques. Localization error (L_{err}) is the positioning error obtained from a localization algorithm. In our simulations, we define L_{err} as

$$L_{err} = {}^{d}\!/_{D} \times 100\,, \tag{4.1}$$

where d is the distance between the actual and computed node's position and D is the inter-node spacing.

4.4. Random Deployment

I ran several simulations to observe the dependence of anchors and events on passive localization.

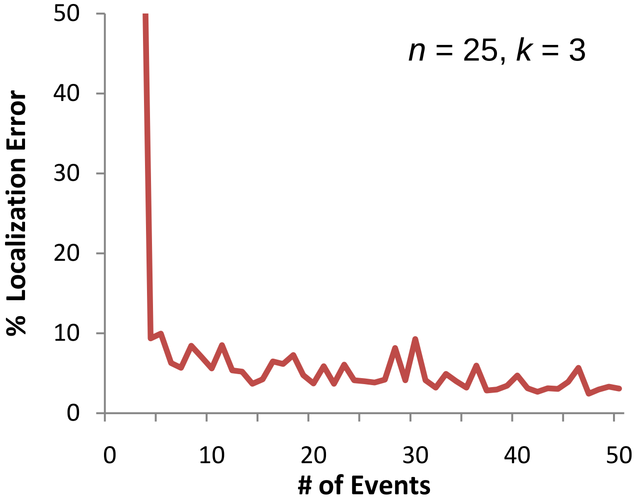

Figure 4.1. Dependence of number of events on localization, obtained from deployment of nodes at random locations.

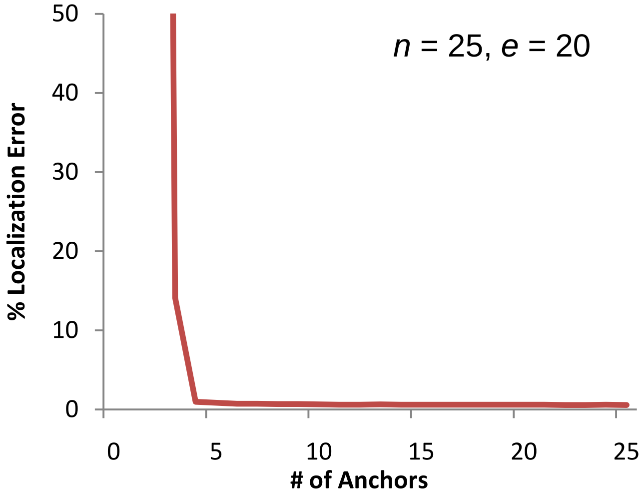

Figure 4.2. Dependence of number of anchors on localization, obtained from deployment of nodes at random locations.

In these simulations each result was obtained from an average of 3000 simulations. In each simulation, about 50 events and 25 nodes were randomly scattered in a network. To look at the dependence of number of events on localization, three anchor nodes were randomly chosen at each time. As we can see in Figure 4.1, the localization improves as we increase the number of events around the sensor network. We can also see that increasing the number of anchor nodes improves the localization. The localization could not be improved further after 5-6 anchor nodes. Moreover, using additional anchor nodes provides no further benefit unless redundancy or fault tolerance is considered.

The following section investigates the effect of sparse (less dense) networks on anchor node placement.

4.5 Manual Deployment

I simulated passive localization on a network of 25 nodes arranged in a 5 x 5 array as shown in Figure 4.3. The locations of the anchor nodes were manually fixed.

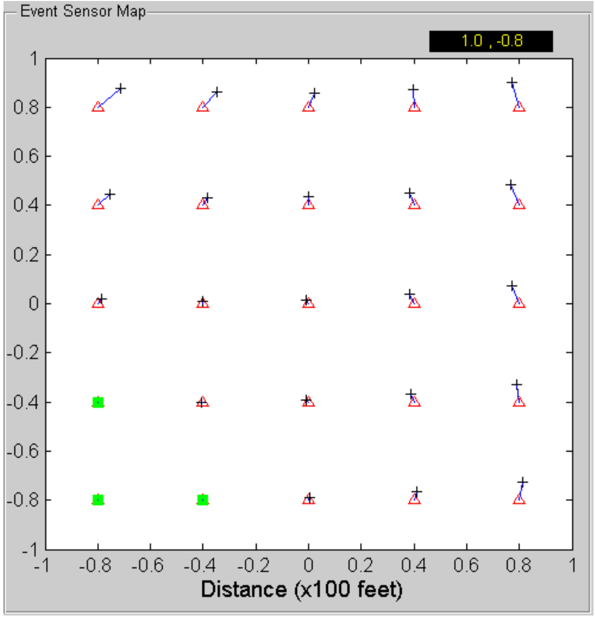

Figure 4.3. Localization of a sparse network with anchor nodes (squares) at a corner of a sensor bed containing sensor nodes (triangles) and their estimated positions (crosses) (L_{err} = 15.52%)

As we can see, the sensor nodes that are far away from the anchor nodes are prone to localization error. The localization error (L_{err}) of 15.52% can be seen in the above setup. The localization error decreases when the anchors are placed on the perimeter (Figure 4.4).

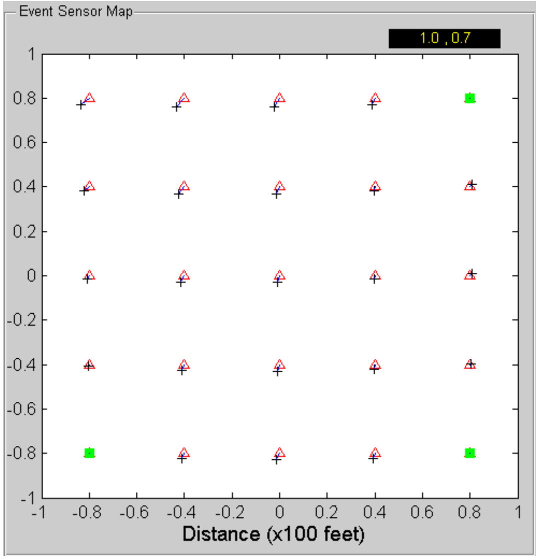

Figure 4.4. Localization on a sparse network with anchor nodes deployed on the perimeter of the sensor bed (L_{err}= 9.68%).

Surprisingly, the localization improved when the anchor nodes are fixed around the center (Figure 4.5). This may be due to the global events occurring at a large distance from the network. This may cause the signals to traverse parallel from the same event. Due to this, the difference in projected distances would be approximately proportional to the physical separation between the nodes.

I then scaled up the sensor network to accommodate 81 sensor nodes in a 9 x 9 array. This time, I used 4 anchor nodes. I first placed these anchor nodes at the perimeter of the network to observe the localization. The localization error was about 18.63% (Figure 4.6) as compared to 12.24% when anchors were placed at the center (Figure 4.7).

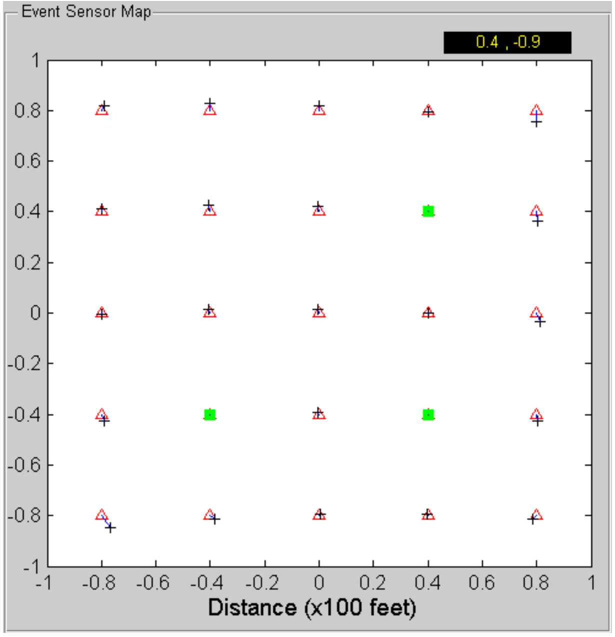

Figure 4.5. Localization on a sparse network with anchor nodes deployed at the center of the sensor bed (L_{err}= 5.75%).

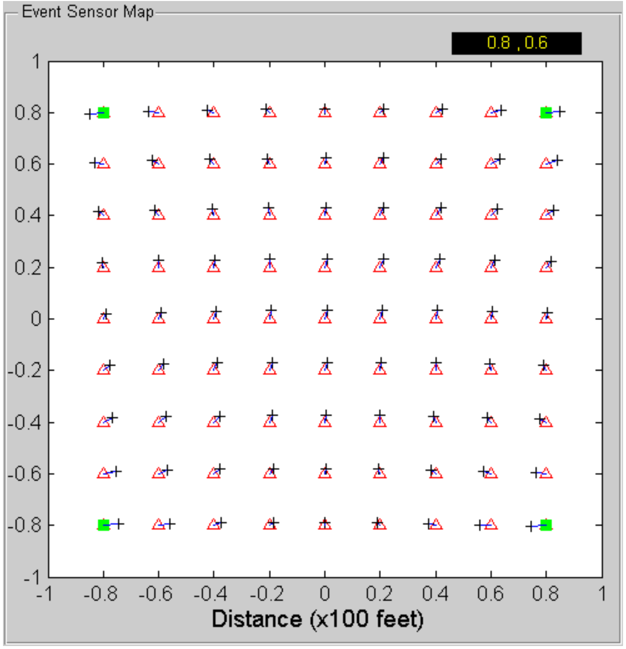

Figure 4.6. Localization on a dense network with anchor nodes deployed at the perimeter of the sensor bed (L_{err}=18.63%).

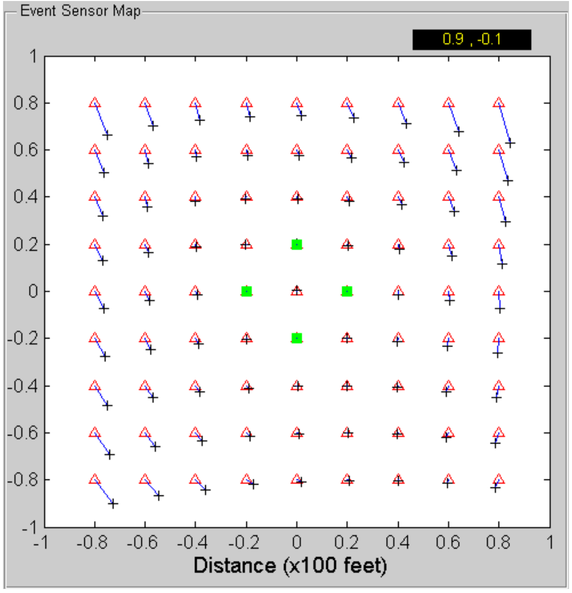

Figure 4.7. Localization with anchor nodes deployed at the center of the sensor bed (L_{err}= 12.24%).

The localization became very erroneous when the anchors were placed at a corner (Figure 4.8). Better localization is achieved when the anchors are placed at the center of the sensor network. I then wanted to study, how the anchor nodes should not be placed for effective localization.

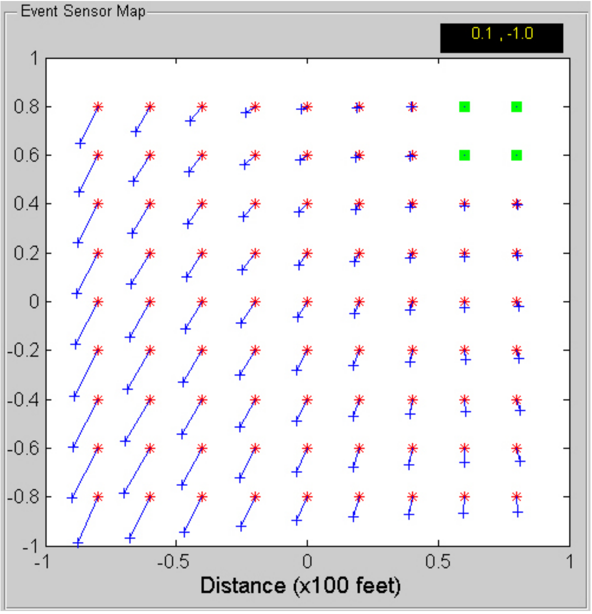

Figure 4.8. Localization with anchor nodes deployed at the corner of the sensor bed (L_{err}= 43.75%).

I could see that anchors should never be linearly related. I tried placing 3 anchor nodes at the center of the network which gave rise to erratic localization (Figure 4.9).

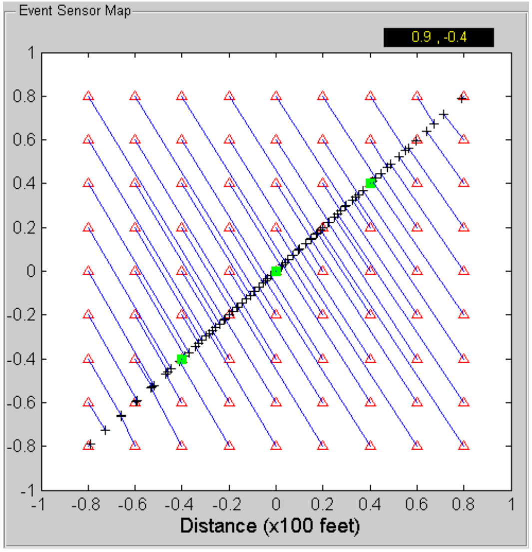

Figure 4.9. Localization with anchor nodes deployed linearly around the center of the sensor bed (L_{err} = 586.54%).

I then tried increasing the angle between the anchor nodes and hence increasing the non-linearity between them, which resulted in much better localization of L_{err} = 14.92% (Figure 4.10).

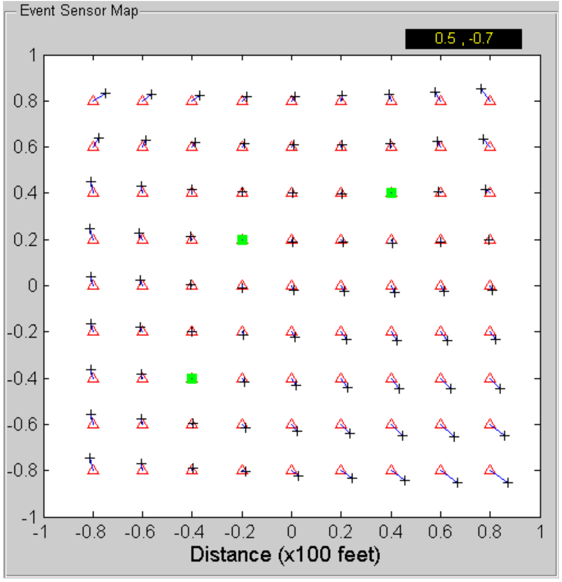

Figure 4.10. Localization with anchor nodes deployed non-linearly around the center of the sensor bed (L_{err} = 14.92%).

Placing anchors at an acute angle (Figure 4.11) ended up with localization (L_{err} = 14.11%) similar to the previous one.

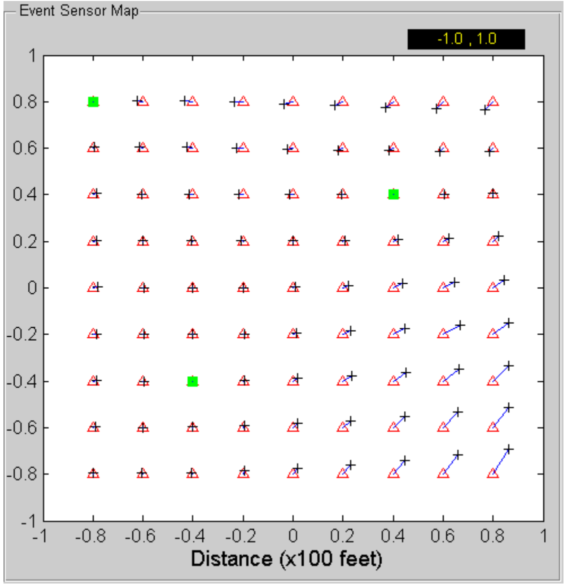

Figure 4.11. Localization with anchor nodes deployed at non-linear positions (L_{err} = 14.11%).

Placing the anchors at a right angle (Figure 4.12) gave better localization (L_{err}= 11.57%).

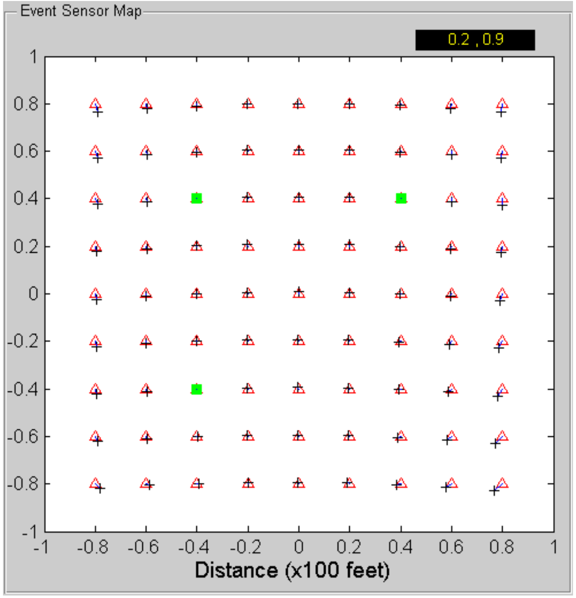

Figure 4.12. Localization with anchor nodes deployed at right angled positions (L_{err}= 11.57%).

I then introduced an anchor exactly in between two anchors (Figure 4.13), which gave rise to similar localization (L_{err}= 11.32%) as before.

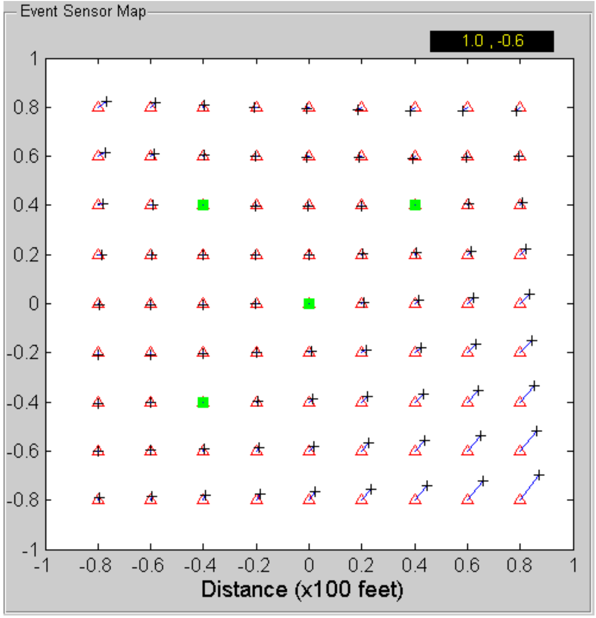

Figure 4.13. Effect of an extra anchor node on localization (L_{err}= 11.32%).

Increasing the number of anchor nodes with a linear relationship was ineffective (Figure 4.14).

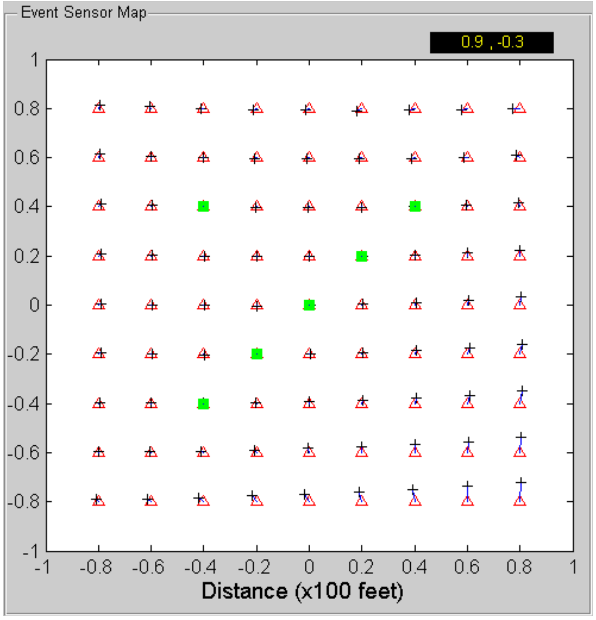

Figure 4.14. Localization with extra anchor nodes deployed at linear positions (L_{err}= 11.54%).

4.6. Conclusion

In this study, I have investigated the effect of the position of the anchor node on localization in sensor networks implementing passive localization. Our simulation studies show that, for effective passive localization, the optimal placement of the anchor nodes is at the center of the network in such a way that no three anchor nodes share linearity. The more the non-linearity, the better the localization. However, the localization for the above networks seemed to be the best when the anchor nodes are placed at right angles. The positioning works on both sparse and dense networks.

Placement of anchor nodes may not be always same, since real sensor networks may not have a uniformly separated matrix like topology as I used in simulations. Placing the anchors in the center in a shape similar to the network may produce better results to minimize localization error.

CHAPTER 5

CONCLUSIONS

5.1. Summary

Proper positioning of anchor nodes is necessary for effective passive localization of Wireless Sensor Networks. I conducted several simulations and studied various positioning strategies for anchor nodes considering parameters like geometry and density of the anchor nodes deployed.

In Chapter 2, different localization systems were described. I then discussed the challenges involved in localization. I also reviewed various existing localization techniques and their pros and cons. Time of Arrival technique was considered to be more accurate and practical compared to other localization techniques.

In Chapter 3, I introduced and discussed passive localization, which uses the time differences between global events for localization. I then discussed the importance of anchor node's position and strategies associated with placing anchor nodes considering different parameters.

In Chapter 4, I presented our Graphical User Interface developed using Matlab. Simulation results for random and manual deployment were shown and discussed. Dependence of various parameters on localization was demonstrated using simulation results from random deployment. I then carried out simulations on sparse and dense networks. The localization error kept increasing with the linearity of anchor node's positions. The localization was unaffected when the anchor nodes were placed within the sensor bed.

5.2. Future Directions

There are several ways this study could be extended:

(a) Implementation on Motes: Passive localization can be implemented on real motes running on TinyOS. Motes which are marked as anchor nodes can be placed at known locations to validate our simulation results.

(b) Third dimensions: Sensor nodes may not be always deployed on a perfect plane. Our study can be modified to study the effect of positioning in three dimensional spaces.

(c) Time synchronization: I assumed all the clocks in the sensor nodes to be synchronized. This may not be the case in real world. Therefore, one can implement time synchronization algorithms along with our study.

(d) Other global events: Our study assumes the source of global events to be static. One can modify the algorithm to accompany mobile sources. For example: sound of an airplane moving over the sensor bed.

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