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Localization Approaches and Methods in Wireless Adhoc Sensor Networks

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Abstract

"Localization Approaches and Methods in Wireless Adhoc Sensor Networks" is a Tracking the location of a person within a premises manually is a less effective and time consuming task. This project aims to develop a system to track location of an elderly/handicapped person or a patient in an indoor environment. In this system there are multiple esp32 devices placed at fixed positions and one esp32 device given to the person whose location is to be determined based on BLE (Bluetooth Low Energy) signals being transmitted. The alerts will be generated based on the person's location and concerned authorities can take the required actions.

1. Introduction

Identifying the accurate position of any node in WSNs has been a major challenge over years. This problem arises due to random deployment of nodes in these networks. Localization is related to estimation of location of nodes. This estimation is done with respect to some coordinate system. Localization is required to identify the location of occurrence of an event, for routing and resolving queries related to the network coverage. Even collaboration depends upon node localization so that several other functions like signal processing, communication, time synchronization, sensors repositioning, energy savings, calibration and heuristics etc. could be accomplished. In most of the applications, the collected data by the network without the information of the location is not useful. However, due to set constraints make this difficult. These common set of constraints include: small size and limited power of sensor nodes, unreliable communication between nodes and limited communication between nodes in a close vicinity defined by the range of communication media. These constraints coupled with various physical characteristics of WSNs, node mobility and total number of anchor nodes required for localization may further complicate the process. However, these limitations are overpowered by the significance of localization in various WSN applications. Consequently, comprehensive research pertaining to localization has been done in the past.

In this paper approaches, techniques and protocols related to localization are discussed with intent providing adequate information so that they can apply or develop techniques, using which issues related to this domain can be addressed.

Subsequent section in this paper identifies the criteria for classification of time synchronization protocols and approaches followed by an explanation of widely used time synchronization protocols along with their advantages and limitations. In section 2, a review of localization approaches and techniques are covered. Section 3 covers an overview of localization algorithms and their classifications.

2. Localization Approaches

The problems regarding estimation and computation of the location (geographical position) of the sensor nodes come under the purview of localization [1, 5, 7, 31-33]. It is a mechanism to discover and build the spatial relationships among nodes, autonomously [4]. It can also be referred to as the identification of location by the estimation of the positional or spatial co-ordinates of the sensor nodes [6, 11]. Putting it differently, it refers to the creation of a map of a wireless sensor network through determination of the geographical coordinates of every node [10, 30]. It is practically impossible to record the location of every sensor node during the deployment of WSN. This is due to several reasons like huge number of spatially distributed nodes, variations in deployment pattern, physical method of deployment etc.

One of the easiest ways of accurate node localization is the use of GPS receivers. But the feasibility of such a technique is doubtful because of high cost incurred, high power consumption and incompatibility with the sensor size. Also, the performance of the GPS reception is highly affected by the indoor and the outdoor deployment. Due to these limitations of GPS, a large number of methods to identify the location of nodes in WSNs have been suggested [12-27].

The importance of localization in WSNs is indispensable. Hence, localization of nodes is one of the major challenges affecting the design and performance of WSNs [2, 33]. It is highly desirable that the localization mechanism for the WSN's to be low cost, accurate, precise, scalable and efficient [3, 5, 31].

Over a period of time, various solutions have been recommended by the researchers to address the issue of node localization [12-27]. Based on the application environment, a tradeoff is often considered between the accuracy in localization and the computation intricacies of the technique used. Hence, such algorithms are preferred that finds the location of the sensor nodes, automatically [28].

The existing approaches to location discovery comprised of two main phases: estimation of distance (or angle) between two nodes and combination of such distances (or angles) [2].

2.1 Distance Estimation Methods

The most widely used methods for distance estimation are given below:

2.1.1 Received Signal Strength Indicator (RSSI): This method fundamentally estimates the strength of the received signal at the receiver end as it is lower than the actual signal transmission strength. This is due to losses during signal propagation. Consequently, this loss is translated into a distance estimate by using analytical and empirical models.

2.1.2 Time of Arrival and Time Difference of Arrival (ToA, TDoA) : Such methods are based on the recoding of time of arrival or time difference of arrival. Based on the known speed of signal propagation, this time of propagation can be used to calculate distance. Such methods are applicable to a variety of signals like RF, infrared, acoustic and ultrasound. The accuracy of such methods is high under the conditions of line of sight but the 34 difficulty arises in meeting such ideal conditions. Moreover, the speed of acoustic signals in air depends upon climatic conditions especially temperature and humidity that in turn brings inaccuracy into the distance estimation.

2.1.3 Angle-of-Arrival (AoA): This method is based upon the angle estimation of received signals. Elementary geometric relationships are then used for calculating the positions of the node. Largely, the results obtained by AoA methods are more precise than RSSI based methods but the hardware cost increases in the use of the former one.

2.2 Localization Techniques

In the next phase, the most widely used methods involve:

2.2.1 Hyperbolic Trilateration: It is the most fundamental and intuitive method in which a node is located through the calculation of the meeting point of the three circles.

2.2.2 Triangulation: Triangulation is used where node’s direction is to be found rather than the distance, as done in AoA methods. By using trigonometric functions and laws, the position of node is calculated.

2.2.3 Maximum Likelihood (ML) Estimation: It minimizes the differences between the calculated and the estimated distances in order to estimate the position of the nodes.

3. Localization Algorithms Localization is a progressive research area with several surveys available on it [3-9, 11, 36, 42, 53, 48, 49]. In the introductory years of development of localization in WSNs, mainly the then existing algorithms on localization were divided only into two types: algorithms based on range and algorithms free from range. But over a period of time, with the expansion of number of algorithms, the classification of such localization algorithms also got enhanced.

3.3.1 A Novel Classification of Localization Algorithms

With a new viewpoint, a reclassification of localization algorithms into four categories was done based on the state (static or mobile) of landmarks and unknown nodes, as it was assumed that the existing classifications were not enough for feeding further researches in localization without taking into account the state (static or mobile) of sensor nodes [52]. The authors called a node as a landmark whose location information can be obtained on its own through a GPS or through some other artificial deployment; otherwise they called it an unknown node. The new classification is as follows:

- Landmarks and Nodes (Both Static)
- Static Landmarks with Mobile Nodes
- Mobile Landmarks with Static Nodes
- Landmarks and Nodes (Both Mobile)

Landmarks and Nodes (Both Static) : Algorithms that are range based require distances calculation between unknown nodes and landmarks while algorithms that are range free does not require the measurement of the distances or angles between the unknown nodes and landmarks for location estimation, rather they use the information regarding connectivity, energy consumption or area of the superimposed region of the landmarks for estimating the distance between two nodes.

- Range Free Localization Algorithms Over a period of time, range free localization algorithms were further grouped into following types, based on Connectivity [56, 66], Centroid [55, 67,68, 57], Energy Attenuation [69,70,71] and Region Overlap [72,73,74].

- Range Based Localization Algorithms Likewise, range based localization algorithms were also further classified based on four categories: Bionics [83,58], Verification [74,84], Landmark Placement [85,86] and Landmark Upgrade [87,88].

Static Landmarks with Mobile Nodes: In real time application of WSNs that are closely related to our lives like habitat monitoring, many unknown nodes are mobile. Therefore, localization algorithms that are based on static landmarks and mobile nodes are divided into historical information based localization algorithms [89-92] focusing on historical information of unknown nodes and the cluster based localization algorithms [93] focusing on the interaction between the landmarks.

Mobile Landmarks with Static Nodes: Such algorithms use mobile landmarks for locating static nodes as per a specified path. These are divided into geometry based localization algorithms [94,95] and path planning based localization algorithms [96-100].

Landmarks and Nodes (Both Mobile): The process of localization involved in these algorithms is intricate as the unknown nodes as well as the landmarks are mobile. These localization algorithms are further classified based on time [101,102] and probability distribution [67, 76].

3.3.2 Classification of Localization Approaches

Another common categorization available in literature [7, 8, 29,30, 63-65] divides the algorithms into the following major categories.

- Centralized vs. Distributed
- Anchor (Landmark) based vs. Anchor (Landmark) free
- Fine Grained vs. Coarse Grained
- Incremental vs. Concurrent
- Range based vs. Range free

A detailed description of the algorithms in each of this category is presented in this following sections.

Algorithms Based on Centralized Approach: In algorithms that follow a centralized approach, a central processor is used for collecting the information from each of the sensor node. Such a model is often problematic when the entire process shuts down in the case of computing server failure. Although, this algorithm reduces the computation problem in each node, it is quite complex with the computational intricacies. At the same time, this algorithm is very costly as the power supply for data transmission from the node to the central device is limited [6].

Some of the techniques that are based on this model are discussed below.

- **Multi-Dimensional Scaling (MDS) -MAP:** This technique analyses the data and visualize information for displaying the distance by calculating the shortest distance among each possible pair of nodes, henceforth, forming a distance matrix to apply MDS for constructing the map of the relative location of nodes. It is capable of reconstructing the relative map of the network, even in the absence of the anchor nodes. The major limitation of this technique lies in its requirement of the global network along with a huge cost of computation and communication [46,80].

- **Simulated Annealing Based Localization:** Simulated annealing is a method of combinatorial optimization that is actually a generalization of Monte Carlo simulation, which tries to find the solution of minimizing functions involving several variables. This algorithm utilizes the analogy between the cooling and freezing process of metal into the minimum energy crystalline structure and transforms an unordered solution into highly optimized solution [47].

- **A RSSI-based localization:** RSSI (Received Signal Strength Indicator) is a distance estimation technique that computes the strength of the received signal using little resources without requiring extra hardware for calculating the distance between two nodes lying within the transmission range [15, 28, 81, 84].

Algorithms Based on Distributed Approach: Distributed (decentralized) localization algorithms guarantee the asymptotic localization of all localizable nodes and provides better scalability [2]. In such techniques, each node communicates with other closer nodes for the location information, in a controlled way. All the necessary computations are done on the nodes themselves where the communication between each pair of node is done for getting their accurate position in the network [2,51]. One of the techniques based on this model is discussed below.

- **Beacon-Based Distributed Algorithm** : In this approach, unknown node's location is estimated from the position of the beacon nodes where all the necessary computations are done on the nodes themselves. Beacon based approaches are categorized into diffusion, bounding box and gradient approach [2, 6].

- **Relaxation Based Distributed Algorithm:** These algorithms use two models or approaches namely, spring model and cooperative ranging approach. Spring Model is an algorithm free from anchors has been suggested where a node is randomly assigned a coordinate [111]. A consistent solution is attained only through local node interactions. This algorithm consists of two parts. A node is assumed to be point masses that are connected through strings that use methods based on relaxation directed by force, for attaining the least energy configuration. Cooperative ranging approach approach starts with assuming the coordinates of the unknown node [113]. The errors are compensated and corrections are made to the redundant calculations, with the availability of more and more information.

- **Coordinate System Stitching:** This category uses two approaches namely, cluster based approach and building a global coordinate system in order to estimate location. The cluster based algorithm algorithm is proposed based on the ability of the unknown nodes to estimate their distances from the nodes lying in their vicinity [118]. The approach consists of two stages. The first is cluster localization in which each node's position happens to be the mid-point of the cluster and relative position of its neighboring nodes can be estimated correctly. In the second stage of cluster transformation, each node's position is shared in the local coordinate system. The node transformation may take place by rotation, translation and reflection, till the number of non-collinear common nodes between the two localizations is at least three. The advantage of this approach lies in its ability to insert a node dynamically. At the same time, the approach may not be able to locate a significant number of nodes under the situation where connectivity among the nodes is low or the measurement noise among them is high.

In the latter method, using stationary nodes and using inter node distance coordinate system stitching can be used to define spatial relationship between nodes in WSNs. This map along with distance matrix can reduce the disparity between nodes by applying coordinate transformation techniques [114]. This algorithm utilizes the same approach and does not require anchor nodes for localization but may converge very slowly in traditional communication model.

- **Hybrid Localization:** Localization scheme composed of Multi-Dimensional Scaling (MDS) and Proximity Distance Mapping (PDM) is a combination of two different localization schemes, i.e. multidimensional scaling and proximity distance mapping [115]. Initially, few anchor nodes are deployed called primary anchors. In the first stage, few sensors that are localized through MDS are taken as secondary anchors. Nodes that do not fall in both of these categories are called as normal sensor nodes. In next stage, these normal sensor nodes are localized through PDM.

Simple Hybrid Absolute-Relative Positioning (SHARP) scheme consists of three phases and uses a combination of two localization techniques i.e. MDS and APS [116]. Firstly, a random selection of a set of reference 43 nodes is done at the network perimeter. Secondly, these reference nodes hence selected are localized through MDS by the computation of the shortest-path distance between each pair of them and then applying MDS for the construction of the relative map. After the completion of previous phases a set of nodes is obtained whose coordinates are known. In the last phase, the remaining nodes of the network are localized through APS, treating the reference nodes as anchors. For estimating its distance from the anchors, information regarding the shortest-path is used by each node. Subsequently, multilateration is performed for estimating its position.

- **Inductive and Deductive Approach Based Localization:** This algorithm is basically based on two different approaches, i.e. deductive and inductive, and is applicable for the indoor environments [117]. The former takes into consideration the physical characteristics related to signal propagation, information regarding the environmental topology and the accurate location of the base stations. Whereas, the latter requires the signal strength at every location to be learned by the whole system first, while this phase may found very expensive and the complexities of the indoor environment hardens the job of the propagation model. In the indoor environment with the presence of many physical obstacles, the deductive methods are highly challenging to be improved as they estimate the location based on real mathematical measures learned from the training phase. In [116], a hybrid localization algorithm is presented with a novel stochastic approach based on deductive and inductive techniques.

- **Radio Interferometric Positioning System (RIPS) based Localization algorithm:** This makes use of two transmitters for directly creating the interference signal [43-45]. In case of the common frequencies of the two transmitters, the resultant signal would possess a low frequency envelope whose measurement is readily possible by the simple hardware present on the node. However, a relative phase offset of the signal at the two receivers takes place due to lack of nodes synchronization. Although with the increased number of measurements, the reconstruction of the node's relative location is possible in 3D. This is a nondeterministic polynomial time (NP)- Complete problem that was optimized for the global solution using genetic algorithm approach [45], while the search space was reduced using RSSI readings [44].

- **Error Propagation Aware (EPA) Localization:** This algorithm is an integration of path loss model and distance measurement error model [46].

Anchor (Landmark) Based Algorithms : Anchor nodes are the nodes that have got their location information beforehand. The algorithms that are anchor based provide a starting point using the anchor node location and finally end with the global coordinates of the nodes. Such algorithms assume that error in localization is inversely proportional to the density of the anchor nodes, meaning, higher the number of anchors, higher the accurate reference points. At the same time, the increase in number of such nodes with extra resources increases the system cost. Till date, the techniques based on distance estimation have not been proved accurate so far, hence preference is being given to global coordinates over local ones, resulting focused study towards anchor based localization.

Anchor (Landmark) Free Algorithms: Anchor free algorithms are based on measuring distance between nodes so that a local map of the nodes is being created. This map thus created is not distinct. By using translation, rotation or flipping they can be attached to any coordinate system [80].

Fine Grained vs Coarse Grained: Fine grained localization algorithms are applicable where the RSSI based features are to be exploited whereas coarse grained algorithms do not take that into consideration [78, 119]. In fine grained localization, the nodes estimate their position by measuring their distances or angles with respect to the neighbouring nodes. This measurement might be erroneous.

Coarse Grained In coarse grained localization, the nodes are capable of only detecting their neighbouring nodes but are having no distance information regarding them, except for the connectivity information. Although high location accuracy is attained through fine grained localization, it often results in tedious calculations and partially high traffic of the WSN. Nonetheless, the accurate locations are not always needed. Generally, a deviation of seven percent is assumed to be acceptable that can be very well achieved through coarse-grained algorithms requiring lesser computations with low traffic of the network [120].

Incremental: Incremental localization algorithm is based on the beacon node. As discussed earlier, a beacon node is a point of reference for an unknown node. This algorithm works by first locating the nodes lying in the vicinity of the beacon node and then locating the far off nodes gradually. The limitation of this algorithm lies in the probable accumulation of measurement error that advances with the process, overall resulting in inaccurate coordinate assignments. For balancing such error, few incremental schemes apply global optimization phase at a later stage, 45 but it always remains a challenge to plunge out of local minima that is introduced by the local optimization in that phase.

Concurrent: Concurrent algorithm works by calculating the position of all the nodes concurrently; meaning at the same point of time.

Range Based Algorithms: These are based on range are proved to be more accurate than range free ones, but the hardware requirement is also more in the former, hence increases cost and size [77]. Techniques that are based on range involve measurement of distances or angles for estimating location. Techniques like Received Signal Strength (RSS) [59], Time Difference of Arrival (TDoA) [60], Time of Arrival (ToA) [61] or Angle of Arrival (AoA) [62] are based on range. On the other hand, range free algorithms use connectivity and topology information for location estimation of a node. Techniques like DV-HOP, Centroid method etc. are based on range free approach.

One more classification, i.e. GPS based vs. GPS free is added along with the above three [78]. In GPS based algorithms, all the nodes are equipped with GPS that ensures location accuracy of all the nodes, but this doesn't prove to be the best solution as it fails to work indoors or under dense foliage due to line of sight obstruction. Although, the location accuracy is very high but proves to be too costly because of GPS and its antenna. On the other hand, in GPS free algorithms, only some nodes are attached with GPS called Anchor or Beacon nodes that are responsible for the initiation of the localization process and use connectivity information for measuring the distance between the nodes relative to local network [79].

Range Free Methods: Most of the localization algorithms are application specific with their advantages and limitations. Localization methods that are range free utilize network topology for localization of node. Although, range based approaches may be more accurate but range free approaches are preferred over them in many applications as they are economical and require no extra hardware [103]. The energy consumption is either same or better than the most of the other range based methods [48].

The most popular range free approaches include DV hop, hop terrain, centroid localization algorithms, APIT and gradient algorithm [49], of which some have been discussed earlier. In DV hop, firstly, each anchor node calculates the average hop distance from other two anchors and broadcasts it. The average hop distance is received by an unknown node from its nearest 46 anchor. Using this distance and its hop distance from all the anchors, it calculates its distance from each one of them. Lastly, it estimates its coordinates through triangulation [76]. For the estimation of initial distance, the approach used by hop terrain is quite similar as that of DV hop. Based on this estimated initial distance, an initial location is attained that subsequently is refined by interchanging information amongst its neighbours in order to ensure location accuracy [103]. In centroid localization algorithms, the location information of the anchors is broadcasted to the unknown nodes that fall on the centroid of the polygon so formed by nearby anchors [104-107]. In Approximate Point in Triangulation (APIT) method, a point in triangulation (PIT) is executed continuously in order to find out that whether a triangle is formed by the anchors or not upon receiving the beacon message from the anchor node. For estimating the unknown node's position, the calculation of centre of gravity is done [107]. Whereas, in gradient algorithm, the shortest path distance between unknown node and the anchor node is calculated by the former, once it receives the beacon message from the anchor. Subsequently, this unknown node uses estimation of error and multilateration to determine its location [112]. DV hop algorithm estimates the coordinates of an unknown node in three phases. In the first phase, each anchor broadcasts its coordinates and hop distance is initialized to one. At the end of each phase, each node has the minimum hop count to all anchor nodes. Secondly, each anchor calculates its average hop distance from the other two and broadcasts this information. Using the information in first two phases, each unknown node estimates its coordinates using triangulation. Several improvements have been suggested in one or more of these phases of DV hop algorithm to improve its accuracy. Experimental and simulation results have shown that localization accuracy can be improved in three ways. Firstly, by adopting a different average hop calculation method in 2nd phase, secondly, by using a different coordinate estimation method in 3rd phase, and lastly, by changing the methods adopted in the last two phases.However, in order to distribute information related to anchor coordinates in the first phase and average hop size calculation by each anchor node in the second, the energy efficiency remains the same as classical DV- Hop algorithm as they also use the same flooding process in first two phases. The ranging technologies used in range based methods lead to errors. Mitigation of errors should be given due consideration apart from the other issues, like cost, in WSNs. The very essence of a localization problem lies in minimizing this error. In an isotropic dense network, the DV-Hop localization algorithm achieves precise results but lack precision in the case of random distribution network. Better results from this algorithm are only expected when the true distances are closer to the estimated ones that is actually not the case in the real time applications. Secondly, when the distance between the unknown node and the anchor node is more, the number of hops between them is also greater. Since the error term is present in the average distance per hop, the increase in the hop counts automatically increases the error in the estimated distance.

Several other approaches utilizing PSO (Particle Swarm Optimization) algorithm, where the node's position is revised by converting it into minimization problem of positioning error, were brought forward for reducing localization error [108,109]. A new algorithm called AFSADV-Hop (Artificial Fish Swarm Algorithm DV-Hop) was proposed to overcome the deficiencies of DV Hop and provide a more accurate solution. It has a higher rate of convergence and is capable of solving nonlinear optimization problems so the optimization problem of the average distance per hop could also find a solution while minimizing the positional error caused by it [110]. Some improved DV-Hop algorithms have also reduced the energy consumption by eliminating the need of broadcasting average hop size by anchors. Thus, network is flooded only once when each anchor broadcasts its coordinates, initializing hop count value to unity

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