Chapter 1

Node Localization in Wireless Sensor Networks

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Sensor node localization is one of the most challenging problems in the wireless sensor network field. Although many excellent works have been done for the sensor node positioning issue, it is still an open problem. This chapter tries to give an comprehensive introduction about the sensor node localization in WSN. Starting from the method taxonomy based on the feature of those localization solutions, all three categories including (i) ranging-based, (ii) ranging-free and (iii) event-driven localization are discussed. In addition, the basic ideas for thirteen well-known sensor node localization papers belonging to diverse categories are discussed for giving solid examples. At the end of the chapter, all techniques are summarized, compared and commented.

1.1. Introduction

The geographical location information of each sensor node in the network is critical for many applications,^{1,2} such as battle field detection,^{3,4} animal habitat monitoring,^{5,6} environment data collection^{4,7,8} and etc. This is because users need to know not only what happened, but also where interested events happened. For example, in the battle field detection application scenario, the knowledge of where the enemy comes from can be much more critical than only knowing the appearance of the enemy. In addition, some routing protocols⁹⁻¹¹ are built under the assumption that geographic parameters of sensor nodes are available for routing table building. However, sensor node localization is in fact still one of the challenging open problems, because of extremely demanding requirements for low cost, tiny size and high energy efficiency at the sensor node side. For instance, due to cost and energy issues, GPS, which is the most widely used technique in localization, can hardly be applicable for every sensor node in the networks.

Many excellent ideas¹²⁻⁵³ have been proposed for addressing node positioning in sensor networks. Most of them can be categorized into three classes: (i) range-based localization,¹⁵⁻³³ (ii) range-free localization,³⁴⁻⁴⁷ and (iii) event-driven local-

ization.^{48–53}

Range-based localization approaches are built on top of distance or angle measurements among sensor nodes in the networks. Range-based methods either are costly for using per-node ranging hardware, or requiring careful in-field calibration and environment profiling.^{36,41,54,55}

Range-free sensor node localization doesn't need any forms of ranging. Instead, the location of each node is estimated based on the knowledge of proximity to the anchor/beacon nodes whose location information is known.^{35–37} Range-free localization methods normally have low accuracy, highly depending on the density and distribution of the anchor nodes.

Event-driven localization makes use of localization events which are generated and propagate across the area where sensor networks are deployed. With known time-spatial relationship embedded in the event distribution, the location of each sensor node can be obtained by mapping the time of event detection with the event position at that time instance. Since sensor nodes only need to detect the events and report the detections, event-driven approaches apply an asymmetric system architecture⁴⁹ which significantly reduces the cost and energy consumption at the resource constrained sensor node side.

In the following sections of this chapter, typical solutions for the three categories of localization methods will be briefly introduced, followed by a comparison summary.

1.2. Ranging-based Localization

Range-based localization systems, such as GPS,⁵⁶ Cricket,¹⁸ AHLoS,²¹ AOA,²⁵ Robust Quadrilaterals⁵⁷ and Sweeps,²⁸ have been put into research and practical usage for a relatively long time comparing with ranging-free and event-driven localization systems. The methodology of range-based localization is trying to do ranging among in-field sensor nodes. Namely, ranging-based localization is based on fine-grained point-to-point distance or angle estimation for identifying per-node location. After obtaining ranging results, e.g., distance or angle measurements, geographical calculations can be applied for computing the final position of each target sensor node.

In the following subsections, four types of ranging-based sensor node localization approaches are explained, which are (i) signal strength based ranging, (ii) angle triangulation, (iii) TOA(time of arrival)/TDOA(time difference of arrival) based ranging, and (v) other ranging methods.

Signal strength based ranging^{16,57–62} is a commonly used technique for localization. According to the received signal strength and the signal propagation model, the distance between the transmitter and the receiver can be estimated. As a typical example, RADAR¹⁶(Radar: An In-building RF-based User Location and Tracking System) is an early but famous work for localizing the sensor nodes based on radio

RSSI (Receive Signal Strength Indicator) measurements.

Angle triangulation^{19,25-27} need node pair angle measurements rather than distance measurement. Giving the bearing measurements, triangulation techniques can be used for coordinates computation. AOA²⁵ (Ad Hoc Positioning Systems (APS) using AOA) is an good example for systems using angle triangulation.

The basic idea for TOA/TDOA⁶³⁻⁶⁵ based method is to estimate the distance between the signal transmitter and the receiver through the signal time-of-fly measurements, given the signal propagation speed. Cricket¹⁸ (The Cricket Location-Support System) applies TDOA (Time Difference of Arrival) techniques and achieves good system accurate.

The paper Doppler⁶⁶ (Tracking mobile nodes using RF Doppler shifts) estimates the velocity (movement vector) of the mobile target sensor node according to doppler effects.

In fact, the measurements of signal strength (RSSI), time delay (TOA/TDOA) and velocity speed are only different formats/modalities for distance estimation. After obtaining distance or angle measurements, which are equivalent in geometry, the position parameters can be calculated by geographic computation, which are actually independent with specific ranging methodology.

1.2.1. *Radar: An In-building RF-based User Location and Tracking System*¹⁶

RADAR¹⁶ is an indoor localization and tracking system RF signal strength is used to indicate the distance between the sender and the receiver. This distance information is used to locate the mobile host by triangulation.

Multiple base stations are placed in this system to provide overlapping coverage in the desired area. Every base station periodically broadcasts beacon messages. The mobile device records the base stations' signal strength and sends this information back to base station. Base station estimates the mobile device's location based on the empirical measurements and signal propagation model so as to provide location-aware services and applications.

This procedure can be reversed in a system with more number of base stations than mobile hosts. As shown in figure 1.1, Three base stations are deployed in different places, the mobile host periodically broadcasts beacons and the base stations record the signal strength information. Since RADAR doesn't assume the symmetry of signal strength, the above two approaches won't affect the accuracy of the location and tracking.

During the empirical measurement experiment, the information of signal strength and signal to noise ratio are recorded for four different directions at seventy distinct physical locations. These information can be represented in the form (x, y, d, ss_i, snr_i) , where $i \in \{1, 2, 3\}$ corresponding to the three base stations. Sample mean is used to summarize multiple signal strength samples from a base station.

Two approaches are proposed to determine the best match of the location and

Fig. 1.1. The RADAR System Overview

orientation of the mobile host for a given set of signal strength measurements. One is the empirical method, which uses the location and signal strength data during the off-line empirical measurement. The other method is the signal propagation modeling, which considers the effects of obstacles or walls between the transmitter and the receiver.

In order to estimate the mobile host's location, RADAR uses the *Euclidean distance* to measure the distance between the observed set of signal strength measurements and the recorded signal strength at a set of locations, then choose the one with the minimum distance.

By using the empirical method, the RADAR system can estimate the mobile host's location with very high accuracy. The median distance error is from 2 to 3 meters. But it requires to construct the signal strength data set for the physical environment that the system is deployed. Moreover, when the location of a base station or the physical environment is changed, the data collection process needs to be done again. While the signal propagation modeling approach can address this issue. Although it is not as accurate as the empirical method, it doesn't need detailed empirical measurements, which makes it easier to be deployed.

The indoor environment changes dynamically, various number of people inside the building could also affect the RF signal strength. So more sophisticated method needs be investigated to improve the system robustness and accuracy. One approach is to record multiple sets of signal strength at different times of the day, then the base stations can perform the matching for the newly received signal strength with those pre-recorded data sets.

The design of RADAR provides an indoor localization and tracking system. Un-

like the infrared wireless networks approach, RADAR provides ubiquitous coverage with high accuracy. Both the empirically-determined and theoretically-computed signal strength information is used to triangulate the mobile host's coordinates.

1.2.2. Ad Hoc Positioning Systems (APS) using AOA³⁷

AOA²⁵ is a method to determine the orientation and position of all the nodes inside the ad-hoc network. It is under the assumption that each node has angle of arrival (AOA) measurement capability, which requires either an antenna array, or several ultrasound receivers.

Fig. 1.2. Positioning by Triangulation

Fig. 1.3. Node A infers its bearing to L

Figure 1.2 illustrates how AOA works. Assume node A, B, and C already know their coordinates, node D needs to identify its own location. If node D knows node A, B, and C's coordinates together with the angles $\widehat{BDA}$, $\widehat{ADC}$, and $\widehat{CDB}$, it can calculate its position using triangulation.

In ad-hoc networks, some nodes may be far away from the landmarks. They can only communicate with their immediate neighbors. Orientation forwarding scheme is proposed to propagate the orientation to these nodes. Here orientation means radial, bearing, or both. The term *bearing* refers to the measured angle respect to

the other object. Orientation forwarding scheme works as follows: First, the nodes that are immediate neighbors of the landmarks get their bearing/radials directly from the landmarks. Then for the nodes that are not the landmarks' immediate neighbors, they will use the method shown in figure 1.3 to get their own orientation. The thick black arrow represents the heading of the node. Here we assume that node A, B and C are neighbors of each other. B and C already know their bearings respect to landmark L, which is far away from B and C. If node A knows its bearings to B and C (angles $\hat{b}$ and $\hat{c}$), then A can calculate all the angles in triangles $\triangle ABC$ and $\triangle BCL$. Furthermore, A can get its bearing with respect to L as $\hat{c} + \widehat{LAC}$. After A getting its orientation, A will propagate this information to its neighbors that haven't got their orientations.

Using the orientation forwarding scheme, measurement errors also get propagated. Two methods can be used for reducing the error propagation. One is to use the TTL scheme for the distance vector packets, the other is to use a threshold value to eliminate triangles that have small angles.

The design of AOA provides a method for the nodes to infer their absolute coordinates and absolute orientations in an ad hoc network by communicating with their immediate neighbors. It doesn't require any additional infrastructure. Since AOA uses localized communication protocol, it is scalable to very large networks. The error propagated during orientation forwarding is a major issue that affect the accuracy of the nodes' position and orientation.

1.2.3. The Cricket Location-Support System¹⁸

Cricket¹⁸ is a location-support system for indoor location dependent applications. The beacon nodes periodically sends out combined RF and ultrasound signals. Based on the time difference of arrival between the RF and ultrasound signals at the receiver side, the receiver can calculate its own location. It achieves five design goals: user privacy, decentralized administration, network heterogeneity, low cost, and portion-of-a-room granularity.

The idea of using the signal time-of-flight for distance measurement is intuitive, however in order to make the system work well, there are a lot of issues need to be addressed. First of all, the system is designed to be a decentralized beacon network. Due to being lack of coordination, the RF transmissions from different beacons may collide with each other. This issue is addressed by introducing randomness during the time of beacon transmission.

Since the ultrasonic signals sent out by different beacons are the same, the receiver may perform false correlation between the RF signal and the neighboring beacon's ultrasound. The second challenge is to minimize the RF and ultrasonic interference among neighboring beacons. Two methods are used to address this issue. One is to select proper system parameters to reduce the incorrect correlation, the other is to use listener inference algorithms, which includes three simple algorithms: Majority, MinMean, and MinMode.

Fig. 1.4. Wrong Positioning of Beacons

In order to ensure the listeners to make the correct judgement of their locations, it's important to place a beacon in an appropriate location. Figure 1.4 shows that the listener in Room B may think it is in Room A, since the beacon in Room A is closer to the listener. Centralized solution may overcome this issue, but it needs the listener provides its own information, which may expose the user privacy.

Fig. 1.5. Correct Positioning of Beacons

Figure 1.5 shows a simple engineering solution, which preserves the user privacy and suitable for the autonomously managed environment. The beacon is placed in a location that has fixed distance to the physical or virtual boundary that demarcate two spaces. Such placement ensures the listener to make correct choice when the listener's distance from the boundary is larger than 1 foot.

Comparing to other location-tracking systems such as Bat,²⁹ Active Badge,⁶⁷ and RADAR,¹⁶ Cricket provides location-support service. It preserves user privacy. Its decentralized approach makes the system easier to be managed. It also has a lot of other advantages, such as network heterogeneity, easy to deploy, and low cost. Each component only costs \$10. Since it uses time difference of arrival method to localize the mobile host, the speed of the tracked mobile host can not be very fast. Moreover, it can not identify the orientation of the tracked device.

1.2.4. Tracking Mobile Nodes using RF Doppler Shifts⁶⁶

Doppler Shift Localization⁶⁶ is a ranging-based localization for mobile nodes (i.e., tracking) in sensor networks. The main idea of Doppler Shift Localization is to use the RF Doppler shifts at stationary anchor nodes (called infrastructure nodes) for the estimation of the location and velocity of a mobile node. In order to mitigate the measurement error and deal with abrupt motion change, Doppler Shift Localization adopts the combination of Constrained Non-linear Least Squares (CNLS) and Extended Kalman Filter (EKF).⁶⁶ Figure 1.6 shows the mobile node localization

Fig. 1.6. Mobile Node Localization based on Doppler Shift Measurement

tion based on the RF Doppler Shift measurement. As shown in Figure 1.6(a), a mobile node T and an anchor node A transmit RF signals of frequencies f_t and f_a , respectively. Six anchor nodes from S_1 to S_6 measure the Doppler shift of the interference signal of the frequencies f_t and f_a at their RF receiver. The arrow from each anchor node indicates the vector for the relative speed of S_i and T . With the Doppler shifts and relative speeds of these anchor nodes along with the moving node's speed, Doppler Shift Localization can localize the location of the mobile node according to its movement. Figure 1.6(b) shows the estimation of the velocity at each anchor node after the mobile node moves further. The magnitude of the Doppler shifts measured by S_i depends on the relative speed of S_i and T , which can be calculated by projecting the mobile node's velocity $\vec{v}$ on the line $\overline{TS_i}$. The length of the projected vectors is determined by both the velocity vector $\vec{v}$ and the location of T . Thus, the velocity vectors at anchor nodes are different between Figure 1.6(a) and Figure 1.6(b).

Doppler Shift Localization has the following assumptions: (i) The tracked node cooperates with the tracking system for trivial detection; (ii) The locations of the infrastructure nodes are known as stationary anchor nodes; and (iii) The tracked node and the infrastructure nodes are time-synchronized at a relatively accurate level, such as a few microseconds.

Doppler Shift Localization consists of three phases: (i) Coordination phase;

(ii) Measurement Phase; and (iii) Tracking Phase. During the *coordination phase*, infrastructure nodes are notified to take part in the mobile node tracking in a certain region. They are time-synchronized to allow for the data fusion for the tracking. During the *measurement phase*, the ranging measurement is performed for the Doppler shifts and relative speeds at the anchor nodes which are low-cost sensors, such as Mica2 nodes. During the *tracking phase*, the estimation of the location and velocity of the mobile node is performed based on an Extended Kalman Filter (EKF). When an abrupt change of motion is detected, the Kalman filter state is updated through the Constrained Non-linear Least Squares (CNLS) optimization with the last collected measurements.

Measuring Doppler shifts is a key function in the Doppler Shift Localization. The low sampling rate due to the sensor hardware limitation decreases the frequency of the interference signal, leading to the smaller Doppler shift. Thus, in order to reduce the inaccuracy caused by this smaller Doppler shift, the Doppler Shift Localization proposes a *radio interferometry* to indirectly analyze high frequency radio signals with low-cost sensors.⁶⁶ As shown in Figure 1.6(a), the mobile node T transmits an unmodulated sine wave at frequency f_t and an anchor node A transmits a sine wave at frequency f_a , such that $f_t > f_a$. These two signals interfere with each other and become an interference signal with an envelope frequency of $f_t - f_a$. The signal transmitted by T will be Doppler shifted by Δf_t^i at each anchor node S_i . The measured envelope frequency f_i of the interference signal at S_i is $f_i = f_t - f_a + \Delta f_t^i$ such that Δf_t^i is the Doppler shift and the magnitude of Δf_t^i depends on the relative speed of S_i and T . Due to measurement errors for f_i , the Doppler Shift Localization estimates the location and speed vector of the mobile node by a *non-linear optimization* method called Constrained Non-linear Least Squares (CNLS).

The Doppler Shift Localization provides the tracking more accurate than a simple Extended Kalman Filter (EKF). The EKF provides the good tracking when the mobile node moves at a constant speed without any change of its direction. However, when the mobile node changes its speed and direction dramatically, EKF does not work well. Therefore, the Doppler Shift Localization updates the Kalman filter state for the mobile node tracking using only EKF. On the other hand, when the abrupt change of the movement (called *maneuver*) is detected, a new Kalman filter state is calculated by the CNLS optimization and is used to update the Kalman filter state at EKF. This EKF-CNLS algorithm improves the tracking accuracy by as much as 50% of the regular EKF.

The Doppler Shift Localization can provide more accurate localization of products in a warehouse than passive RFID system providing only the proximity to a reader. Another advantage of the Doppler Shift Localization can easily support the multiple target tracking. The multiple target tracking is possible by letting each tracked node transmit the RF signal at a unique frequency. Therefore, the Doppler Shift Localization is an efficient, indoor/outdoor localization scheme for a cooperative mobile node, transmitting an RF signal for localization.

1.2.5. Remarks for Ranging-based Localization

As it shows in previous sections, AOA and Cricket systems both need special additional hardware such as ultrasound/infrared transmitter/receiver for ranging purpose. Per-node ranging device is costly and energy hungry. Therefore, as in the RADAR and Doppler systems, many range-based methods tried to eliminate expensive or energy hungry ranging devices by assuming and using RSSI^{16,20,24,41,68} with noise filtering and many other advanced algorithms^{22,69-73} for mitigating errors brought about by multi-path fading, background interference and irregular signal propagation. However, recent empirical study^{20,55,74,75} concluded that unless careful calibration and environment profiling can be accomplished, radio ranging irregularity^{36,41,55,75} is detrimental to the system accuracy.

In addition, ranging signals generated by sensor nodes have a very limited effective range because of energy and form factor concerns. For example, ultrasound signals usually effectively propagate 20-30 feet using an on-board transmitter.¹⁸ Consequently, these range-based solutions require an undesirably high deployment density.

All in all, constraints on the cost, energy and hardware footprint of each sensor node make these range-based methods undesirable for massive outdoor deployment.

1.3. Ranging-free Localization

Range-free solutions^{34-38,41} try to estimate the location of each sensor node based on the information of geographic proximity to the anchor nodes whose positions are known. In those solutions, sensor nodes estimate their locations according to the known position information of the surrounding anchor nodes. Different anchor combinations help to narrow the location area where a normal node possibly be located. Anchor-based approaches normally demand high and uniformly distributed anchor density in the network so as to achieve good positioning accuracy. In reality, it is highly appreciated to use as few anchor nodes as possible in order to reduce system cost. Different from some early IR or magnetic sensor based systems,^{67,76-79} newly proposed methods get rid of additional proximity sensing hardware, while only RF is used.

In the following, five ranging-free sensor node localization approaches are briefly introduced, which are Centroid³⁵ (GPS-Less Low Cost Outdoor Localization for Very Small Devices), APIT³⁶ (Range-free Localization Schemes in large-scale Sensor Networks), Connectivity-MDS⁴¹ (Localization from Mere Connectivity), APS³⁷ (Ad-hoc Positioning Systems), and Waling GPS⁸⁰ (Walking GPS: A practical Solution for Localization in Manually Deployed Wireless Sensor Networks).

Centroid and APIT both make use of the proximity information with surrounding stationary position known sensor nodes (anchor or beacon nodes). Connectivity-MDS computes an optimal estimation of the relative node topology based on mere connectivity info among sensor nodes. APS estimates the geographic distance

among sensor nodes using number of communication hops^{42,43} (DV-Hop), and Walking GPS illustrates a simple but effective localization method: using mobile beacons.^{59–61,81–83}

1.3.1. *GPS-Less Low Cost Outdoor Localization for Very Small Devices*³⁵

Centroid³⁵ is an early work for sensor node localization. The idea proposed in this paper is very straight forward. The target sensor node selects k neighboring anchor nodes (k is a variable) with most reliable communication link quality. Then the location of the target sensor node is calculated as the gravity enter of all the selected k anchor nodes, as shown by the following equation.

$$(X_{est}, Y_{est}) = \left(\frac{X_1 + X_2 + \cdots + X_k}{k}, \frac{Y_1 + Y_2 + \cdots + Y_k}{k} \right)$$

1.3.2. *Range-free Localization Schemes in Large-scale Sensor Networks*³⁶

This paper, namely APIT,³⁶ presents a range-free localization for large scale sensor networks. The main idea of APIT is to perform sensor location estimation by isolating the target area into *triangular regions* among beacon nodes.

Fig. 1.7. Area-based APIT Localization

Figure 1.7 shows the area-based APIT algorithm. A sensor node receives beacon messages from the beacon nodes that are anchors. The sensor makes all possible triangles with three anchors among all of the perceived anchors. As shown in Figure 1.7, the maximum overlapping area for the sensor node is computed at first; this intersection area is considered as the possible area where the sensor node is located. APIT then decides the center of gravity of this intersection area as the position of the sensor node.

APIT has the following assumptions: (i) Anchor nodes with location information are deployed along with non-anchor nodes; (ii) The node density is relatively high with connectivity above 6; and (iii) The beacon signal strength attenuates monotonically as the distance between the anchor and the non-anchor increases.

APIT consists of three steps: (i) the Departure Test; (ii) the Approximate Point-In-Triangulation Test (APIT); and (iii) APIT Aggregation. The *departure test* is to check whether a node is further away from an anchor than a neighbor. Figure 1.8 shows the departure test. This test is based on the observation that the

Fig. 1.8. Departure Test for measuring the relative distance

received beacon signal strength at a node is monotonically decreasing according to the distance from an anchor. In Figure 1.8, node M has weaker signal strength for the beacon from anchor A than neighbor N_1 , but it has stronger signal strength than neighbor N_2 . The *APIT test* determines whether a node is inside the triangle for

Fig. 1.9. APIT Test for checking the node's position for anchor triangle

three anchors or not. Figure 1.9 shows the *APIT test*;³⁶ if node M has no neighbor simultaneously *further from/closer to* all three anchors A , B and C consisting of a triangle, M is assumed to be inside triangle $\triangle ABC$. Otherwise, M is assumed to be outside this triangle. Figure 1.9(a) illustrates an example that M is inside $\triangle ABC$ and Figure 1.9(b) illustrates an example that M is outside $\triangle ABC$.

APIT can make mistake in this APIT test due to both the *edge effect* of node M and the *irregular placement* of neighbors. This problem requires a more robust APIT test. APIT provides a more robust APIT test through the aggregation of

multiple APIT tests; this APIT test is called *APIT aggregation*. Figure 1.10 shows

Fig. 1.10. APIT Aggregation based on scan for determining the maximum overlapping area

the APIT aggregation based on a grid SCAN algorithm; for each APIT inside decision, the values of the grid regions are incremented, but for each APIT outside decision, those of the grid regions are decremented. For all of the possible triangles, the APIT test is performed for each grid region and then the maximum overlapping area is obtained. As shown in Figure 1.10, the aggregated area of grid regions with value 2 is the maximum overlapping area. Finally, we can determine the sensor's location with the center of gravity for this maximum overlapping area.

APIT targets at the localization of a static sensor network with high node density. The trade-off exists between the node density and the localization accuracy. Through the aggregated decisions based on this high node density, APIT can provide the good estimation for node location even under the noisy environment for individual APIT test. In order to reduce the cost of the anchor deployment, APIT can use a single moving anchor advertising the beacons at different locations. Therefore, APIT is a range-free localization appropriate to a dense sensor network allowing the coarse accuracy in node location.

1.3.3. Localization from Mere Connectivity³⁹

Localization from Mere Connectivity³⁹ (Connectivity-MDS) is a centralized algorithm that derives the locations of sensor nodes using only connectivity information. Localization from mere connectivity is based on the classical metric multidimensional scaling (MDS), a data analysis technique from mathematical psychology. It works well when there are very few anchor nodes, without constraints on where those anchor nodes are located. Connectivity-MDS can also make use of additional information such as estimated distance between each pair of nodes when it is available.

In Connectivity-MDS, the network is represented by an undirected graph with vertices V and edges E . If estimated distances between neighboring nodes are available, entries in E are associated with such information. Otherwise E only provides connectivity information and consists of only 1s and 0s. As shown in Figure 1.11 where a hundred nodes are placed randomly in a 20×20 field, the

Fig. 1.11. Original Graph

Fig. 1.12. Relative Graph

Fig. 1.13. Final Absolute Graph

all-pairs shortest path matrix P can be computed using E , either by Dijkstra's or Floyd's algorithm.

The relative graph in Figure 1.12 is then obtained by applying classical MDS to P . In classical MDS, P is firstly converted into a double centred matrix B :

$$B = -\frac{1}{2}(I - \frac{1}{N}U)P^2(I - \frac{1}{N}U)$$

Where N is the number of nodes and U is a $N \times N$ matrix with all 1s. Then the coordinates of the nodes X is computed by taking the Singular Value Decomposition (SVD) of B :

$$B = VAV^T$$

$$X = VA^{\frac{1}{2}}$$

From Figure 1.12, the relative graph is shifted and rotated compared with the

original graph. With the known location of the anchor nodes (the solid dots in the figure), the relative graph can be finally transformed to the final graph.

The complexity of Connectivity-MDS is $O(n^3)$. Since it requires very few anchor nodes which are not necessarily well-deployed, it is a promising localization algorithm. However, it has certain limitations. It requires global information of the network since it is centralized. One way to solve this problem might be dividing the network into several sub-networks with three or more anchors within each sub-network. By putting all patches together the final locations of all nodes can be derived. Another drawback is that the performance degrades when the number of anchor nodes is large. One possible solution is to use more advanced MDS algorithm such as anchor point method.

1.3.4. *Ad-hoc Positioning Systems*³⁷

In APS,³⁷ a distributed, hop by hop algorithm named Ad-hoc Positioning System (APS) is proposed to locate sensor nodes within the network. Using the similar idea as GPS, APS requires a number of anchor nodes with known location information. Each node estimates its distance to at least three of those anchor nodes by communicating only with its neighbors, and computes its own position by solving linear systems iteratively.

In the paper, three methods are proposed to estimate the distance from a node to an anchor node: “DV-hop”, “DV-Distance” and “Euclidean” propagation methods.

“DV-hop” works for isotropic network where the properties of the network are the same in all directions, thus distance between node pair is proportional to communication hop count. In “DV-hop”, each node maintains a table with the positions of each local anchor and the least number of hops from each anchor to itself. By exchanging tables with its neighbors, the positions of all local anchor nodes are available in the table, as well as the number of hops away from each anchor. Then each anchor node computes the average number of hops in each direction and distribute such information by controlled flooding, where a node only reads and forwards its first message and ignores all subsequences. An example is shown in Figure 1.14. In this figure, A_1, A_2 and A_3 are three anchor nodes. A_1 is 2 hops away from A_2 and 5 hops away from A_3 so that it computes the average size of each hop as $\frac{40m+105m}{2+5} = 20.7m$. Similarly, A_2 and A_3 computes the average size of each hop as $\frac{40m+60m}{2+3} = 20m$ and $\frac{60m+105m}{3+5} = 20.6m$. All anchors then distribute their estimation to the nodes within the network. Suppose node B receives A_3 's result first, which is $20.6m$. Using this information, B can finally compute its distance from all anchor nodes in its table.

The second method, “DV-Distance”, has the similar idea but measures distance between neighboring nodes directly and propagates distance information in meters instead of in hops. It benefits from the fact that hop count is not necessarily proportional to the real distance. However, it is more sensitive to measurement errors.

Fig. 1.14. The Idea of DV-Hop

The third method, “Euclidean” works well when the topology is non-isotropic. It propagates true Euclidean distance to the anchor node and works only when a node has at least two neighbor nodes that have already had the estimation of distance from a anchor and their distance is also known. By applying Pithagora’s generalized theorem a node can finally estimate its distance from this anchor.

After the distances from several anchors becoming available, a node starts to use the GPS triangulation method to compute its own position. It starts with an initial estimated position and computes the position correction based on the comparison between the distance table and the distance from its current estimated position to all anchors. In each iteration, a linear system is solved by any least square method such as Householder method. The process stops when the position correction is below a certain threshold.

APS has several advantages. First, it is distributed, thus requires no global information and special infrastructure. Second, the propagation methods only require a node to communicate with its immediate neighbors, hence have a low signaling complexity and energy consumption.

1.3.5. *Walking GPS: A Practical Solution for Localization in Manually Deployed Wireless Sensor Networks*⁸⁰

Walking GPS⁸⁰ is a practical and cost effective solution for manually deployed wireless sensor networks. In walking GPS, the deployer (either a person or a vehicle) is equipped with a GPS device which periodically sends broadcasting messages with its current location information. Sensor nodes can then infer their current positions by receiving these messages.

The Walking GPS system consists of two components: the GPS Mote and the Sensor Mote. The GPS Mote receives its global GPS coordinates from the GPS device and transforms the global GPS coordinates into local coordinates in order to reduce overhead. The sending power is limited to ensure that only the nearest sensor

mote receives the broadcasting message. The sending frequency is also associated with the deployment rate. The Sensor Mote, on the other hand, receives local coordinates from the GPS Mote and infer its location information from the message. If, for some reason, a Sensor Mote does not have its own position, it will query for its neighbors' positions and computes its own position by the GPS triangulation procedure.

The walking GPS supports two types of mote deployment. The first type is that each sensor mote is turned on right before its deployment, and the second deployment type is that sensor motes are turned on all the time. For the first type, sensor motes only read the first received message and find their own positions. For the second one, sensor motes should infer their deployment time from the RSSI value of received messages.

From extensive experiments, walking GPS is shown to work very well in manually deployed wireless sensor networks: all sensor motes are shown to be able to locate themselves with an average error within 2m. However, it works only when the sensor motes are deployed manually, which limits its use in many applications.

1.3.6. *Remarks for Ranging-free Localization*

Ranging-free localization methods eliminate per-node ranging hardware, which reduces the overall system cost. The above five ranging-free methods illustrate three types of ranging-free approaches: (i) anchor proximity; (ii) radio connectivity; and (iii) mobile beacon. For anchor proximity based methods, normally a considerable number of anchor nodes is needed for achieving good system accuracy. Radio connectivity based solutions could be affected by the notorious fact of radio irregularity. Mobile beacon is an easy and practical solution, however, it is not applicable in many prohibitive environments where per-node manual deployment is not possible. Overall speaking, ranging-free methods are cheaper than ranging-based methods but with lower system accuracy or limited application scenarios.

1.4. Event-driven Localization

Event-driven localization brings in localization events which are generated and propagate across the area where sensor networks are deployed. According to the pre-known time-spatial relationship embedded in the event distribution,^{48,49} and the sequential detection of the event in the time domain^{52,84} or in the space domain,⁵⁰ the location of each sensor node can be estimated.

In the following, four event-driven sensor node localization methods are summarized, which are SpotLight⁴⁹ (Spotlight: A High Accuracy, Low-Cost Localization System for Wireless Sensor Networks), MSP⁵² (MSP: Multi-Sequence Positioning of Wireless Sensor Nodes), Uncontrolled Events⁸⁴ (Sensor Node Localization Using Uncontrolled Events), and Stardust⁵⁰ (StarDust: A Flexible Architecture for Passive Localization in Wireless Sensor Networks).

SpotLight, MSP and Uncontrolled Events forms three generations of event-driven localization solutions from preciously controlled event distribution to uncontrolled event distribution. All of the above three methods depend on the time-domain sequential detection of the localization events at the sensor node side. Stardust pinpoints the sensor nodes by processing the image of node's reaction to the flashing localization event.

1.4.1. *Spotlight: A High Accuracy, Low-Cost Localization System for Wireless Sensor Networks*⁴⁹

The top level idea of the Spotlight system is to remove all the expensive and energy depletion functions for the localization from the resource constrained sensor node to an external specific localization focused entity the spotlight device. As shown in Figure 1.15, the localization device generates some from of localization events according to certain well defined “Event Function”, and then it receives the detection report from the sensor nodes. According to the time-spacial relationship embedded in the “Event Function”, the spotlight device is able to get the location information of each node. This location info is then feedback to those nodes, so that every node in the network obtains its location.

Fig. 1.15. The Basic Idea of SpotLight System

The asymmetric structure of the spotlight system achieves the goal of low cost of each node, which actually determines the whole cost of the network. The powerful computing capability and abundant energy supply of the spotlight device realizes the configurable high accuracy of the localization. However, in the SpotLight System, the event distribution needs to be both accurate as to time and precise about the space, which adds system cost and results in slow localization speed. Precise event distribution is difficult to achieve without careful calibration, especially when the event-generating devices require certain mechanical maneuver.

1.4.2. MSP: Multi-Sequence Positioning of Wireless Sensor Nodes⁵²

MSP⁵² brings in anchor nodes for event-driven localization. Without depending on rigid time-spatial relationship carried by the localization event distribution, MSP obtains possible location area of each sensor node by processing multiple one-dimensional *node sequences* within which relative position information along the event propagation direction is embedded.

Fig. 1.16. The MSP System Overview

Fig. 1.17. Node Sequence and Map Partition

Figure 1.16 illustrates how the algorithm works. MSP works by extracting relative location information from multiple simple one-dimensional orderings of nodes. Figure 1.16(a) shows a layout of a sensor network with anchor nodes and target nodes. Target nodes are defined as the nodes to be localized. Briefly, the MSP system works as follows. First, events are generated one at a time in the network area (e.g., ultrasound propagations from different locations, laser scans with diverse angles). As each event propagates, as shown in Figure 1.16(a), each node detects it at some particular time instance. For a single event, we call the ordering of nodes, which is based on the sequential detection of the event, a *node sequence*. Each node sequence includes both the targets and the anchors as shown in Figure 1.16(b). Second, a multi-sequence processing algorithm helps to narrow the possible location of each node to a small area (Figure 1.16(c)). Finally, a distribution-based estimation method estimates the exact location of each sensor node, as shown in Figure 1.16(d).

In MSP, each localization event generates one node sequence and each node sequence gives out an partition of the whole area. The whole area can be divided into $O(N^2d^2)$ parts with N anchors and d events. Therefore, With sufficient events and anchors, accurate positioning is achievable. Figure 1.17 shows an example of two nodes sequences created by straight line scan events. Anchor nodes (location pre-known) in two node sequences split the area into 16 small parts, and each target node (needs to be localized) gets its location area according to its ranking in the node sequence.

Several improvements concerning node sequence processing are proposed in the MSP paper, such as Sequence-Based MSP, Iterative MSP, Distribution-Based Estimation and Adaptive MSP, all of which works together enhances the accuracy of the localization results.

The design of MSP provides a trade off between the physical cost (anchors) and soft cost (localization event). So only a few number of anchor nodes are necessary. In addition, the requirement for accurate event distribution control is removed. However, the setup of MSP assumes that accurate control of the event generation is available, e.g., straight-line scan with certain angle. Therefore, MSP is actually a hybrid solution combining anchors and semi-controlled localization events.

1.4.3. Sensor Node Localization Using Uncontrolled Events⁸⁴

The setup of MSP assumes that accurate control of the event generation is available, e.g., straight-line scan with certain angle. In a practical system, control over event generation could be costly and hard. Uncontrolled Events proposed a sensor node localization system design based on totally uncontrolled events. This solution eliminates the control over event generation and event distribution. Therefore, it could significantly improve the flexibility and convenience for system deployment.

There are two levels of control over the localization events: (i) control of how to generate the event, e.g., a straight-line laser beam scan event at certain angle.

This type of control is named as control of *event generation parameter*; (ii) control over event propagation, e.g., keep constant scan line-speed, which is called control of *event distribution*. For randomly generated events, neither of the above controls is possible, and in reality, both levels of control could be hard and costly to achieve.

Fig. 1.18. System Overview

The basic idea for localization using uncontrolled events is to estimate the event generation parameter using anchors in the field, and then shrink the possible location area of each normal node according to the estimated event parameter. In brief, as it is shown in Figure 1.18, the system works as follows. First, certain type of events are generated in the network, e.g., straight-line laser beam scan with uncontrolled angle, direction and speed. As each event propagates, sensor nodes detect the event sequentially at different time instances, which naturally gives out an ordering of in-the-field nodes called *node sequence*. For example, as shown in Figure 1.18(a), a top-down scan event generates node sequence (3 A 1 6 4 8 C 2 B 7 5). Here we use uppercase letters (e.g., A, B, C) denote anchor nodes and numbers (e.g., 1, 2, 3) denote normal nodes. Second, node sequences processing algorithms try to estimate the event generation parameter, e.g., possible scan angle range, by

processing ordered anchor subsequences which can be extracted directly from node sequences as shown in Figure 1.18(b). Third, processing a node sequence with its corresponding estimated event generation parameter, the whole map can be divided into lots of small parts. Each normal sensor node obtains a possible location area, which is composed of different single or multiple parts, according to their ranks in the node sequence. With multiple events, final location area of a normal node could be shrunk dramatically by extracting the joint region of the possible location areas given by all the node sequences. Thus the estimated position could be got from a relatively small location area to achieve good localization accuracy (Figure 1.18(c)).

As the third generation of the event-driven localization method, sensor node localization using only randomly generated events provides excellent system flexibility while adding no extra cost at the resource constrained sensor node side. In addition, localization using uncontrolled events provides a nice potential option of achieving node positioning through natural ambient events.

1.4.4. *StarDust: A Flexible Architecture for Passive Localization in Wireless Sensor Networks*⁵⁰

StarDust,⁵⁰ which works much faster than all of the above three event-driven localization approaches, uses label relaxation algorithms to match *light spots* reflected by corner-cube retro-reflectors (CCR), shown in Figure 1.19, with the sensor nodes using various kinds of constraints. Label relaxation algorithms converges only when a sufficient number of robust constraints are obtained. Due to the environmental impact on the optical event and the RF connectivity constraints, however, StarDust is less accurate than Spotlight.

Figure 1.19 shows the CCR and the sensor node used in the StarDust system. CCR can reflect the light back to its coming direction. Figure 1.20 illustrates an example of the system implementation of StarDust. Figure 1.20(a) shows an stadium in which sensor nodes are deployed. In Figure 1.20(b), when a flashing light spot is generated to illuminate the area with sensor nodes, which is shown more clear in Figure 1.20(c), we take a picture of this area. By computer image processing, a result shown in Figure 1.20(d) can be obtained. This figure indicates that the locations of each sensor nodes can be determined.

Although in the paper StarDust, multiple effective solutions are provided for differentiating the sensor node in the image shown in Figure 1.20(d), it is still a challenging problem in some scenarios.

1.4.5. *Remarks for Event-driven Localization*

Comparing with ranging-based and ranging-free localization methods, event-driven localization methods can achieve tradeoff between system accuracy and system flexibility, between “hard cost” (number of anchor nodes) and “soft cost” (number of localization events). As an relatively new kind of method, event-driven sensor node

Fig. 1.19. CCR and Sensor Nodes

Fig. 1.20. StarDust Example System

localization is now attracting more and more attention from the researchers and considered as the promising solution with good system flexibility.

1.5. Chapter Summary

Localizing the sensor nodes randomly deployed in the network is still an open and challenging problem in the WSN field. It is an open problem because there is not a single solution which could achieve desirable features including good accuracy, low

cost, fast speed, high confidence and etc, simultaneously for all applications. It is a challenging problem because of the extremely limited resource and cost constraints at the sensor node side. This chapter introduces one kind of taxonomy for the sensor node localization methods. However, there are other approaches not belonging to any of the three classes, or crossing multiple categories. Nevertheless, any solution itself is always an issue about tradeoff between system cost and localization performance including accuracy, speed, and etc.

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