LOCALIZATION IN WIRELESS SENSOR NETWORKS

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***Abstract* -** Wireless sensor networks are fundamentally intended to provide information about the spatio-temporal characteristics of the observed physical world. Each individual sensor observation can be characterized essentially as a tuple of the form $< S, T, M >$, where S is the spatial location of the measurement, T the time of the measurement, and M the measurement itself. We shall address the following fundamental question in this paper: How can the spatial location of nodes be determined?

I. *INTRODUCTION*

The location information of nodes in the network is fundamental for a number of reasons:

- To provide location stamps
- To locate and track point objects
- To monitor the spatial evolution of a diffuse phenomenon
- To determine the quality of coverage. .
- To achieve load balancing.
- To form clusters.
- To facilitate routing .
- To perform efficient spatial querying.

II. KEY ISSUES

Localization is quite a broad problem domain [1, 2], and the component issues and techniques can be classified on the basis of a number of key questions.

What to localize? This refers to identifying which nodes have a priori known locations (called reference nodes) and which nodes do not (called unknown nodes). The unknown nodes may be cooperative or noncooperative. Non-cooperative nodes cannot participate actively in the localization algorithm.

When to localize? In most cases, the location information is needed for all unknown nodes at the very beginning of network operation. In static environments. In other cases, it may be necessary to provide localization on-the-fly.

How well to localize? This pertains to the resolution of location information desired. Depending on the application, it may be required for the localization technique to provide absolute(x,y,z) coordinates, or perhaps it will suffice to provide relative coordinates or symbolic locations .

Where to localize? The actual location computation can be performed at several different points in the network: The choice may be determined by several factors: the resource constraints on various nodes, whether the node being localized is cooperative, the localization technique employed, and, finally, security considerations.

How to localize? Finally, different signal measurements can be used as inputs to different localization techniques. The basic localization algorithm may be based on a number of techniques, such as proximity, calculation of centroids, constraints, ranging, angulation, pattern recognition, multi-dimensional scaling, and potential methods.

III. LOCALIZATION APPROACHES

Generally speaking, there are two approaches to localization:

1. **Coarse-grained localization using minimal information:** These typically use a small set of discrete measurements, such as the information used to compute location

2. **Fine-grained localization using detailed information:** These are typically based on measurements, such as RF power, signal waveform, time stamps, etc., that are either real-valued or discrete with a large number of quantization levels. These include techniques based on radio signal strengths, timing information, and angulation. The

tradeoff that emerges between the two approaches is easy to see: while minimal information techniques are simpler to implement, and likely involve lower resource consumption and equipment costs, they provide lower accuracy than the detailed information techniques. We shall now describe specific techniques in detail.

IV. COARSE-GRAINED NODE LOCALIZATION USING MINIMAL INFORMATION

A. Binary Proximity

Perhaps the most basic location technique is that of binary proximity – involving a simple decision of whether two nodes are within reception range of each other. A set of references nodes are placed in the environment in some non-overlapping manner. Either the reference nodes periodically emit beacons, or the unknown node transmits a beacon when it needs to be localized. If reference nodes emit beacons, these include their location IDs. The unknown node must then determine which node it is closest to, and this provides coarsegrained localization. Technique can be of considerable use in practice.

B. Centroid Calculation

The same proximity information can be used to greater advantage when the density of reference nodes is sufficiently high that there are several reference nodes within the range of the unknown node. This simple centroid technique has been investigated using a model with each node having a simple circular range R in an infinite square mesh of reference nodes spaced a distance d apart. It is shown through simulations that, as the overlap ratio R/d are increased from 1 to 4, the average RMS error in localization is reduced from 0.5d to 0.25d.

C. Geometric Constraints

If the bounds on radio or other signal coverage for a given node can be described by a geometric shape, this can be used to provide location estimates by determining which geometric regions that node is constrained to be in, because of intersections between overlapping coverage regions. Although arbitrary shapes can be potentially computed in this manner, a computational simplification that can be used to determine this bounded region is to use rectangular bounding boxes as location estimates. Figure 1 illustrates the use of intersecting geometric constraints for localization. Localization techniques using such geometric regions were first described by Doherty *et al.* [3]. One of the nice features of these techniques is that not only the unknown nodes can use the centroid of the overlapping region as a specific location estimate if necessary, but they can also determine a bound on the location error using the size of this region. When the upper bounds on these regions are tight, the accuracy of this geometric approach can be further enhanced by incorporating "negative information" about which reference nodes are *not* within range [4].

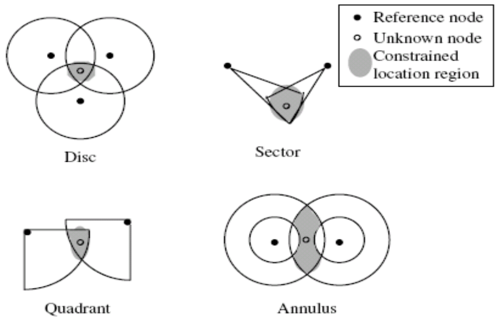


Figure 1 Localization using intersection of geometric constraints

D. Approximate Point In Triangle (APIT)

A related approach to localization using geometric constraints is the approximate point-in-triangle (APIT) technique. APIT is similar to the above techniques in that it provides location estimates as the centroid of an intersection of regions. Its novelty lies in how the regions are defined – as triangles between different sets of three reference nodes (rather than the coverage of a single node). This is illustrated in Figure2.

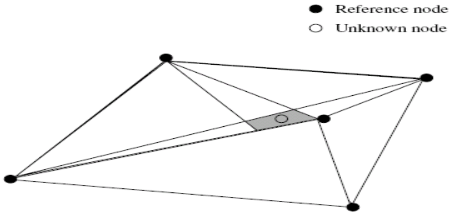
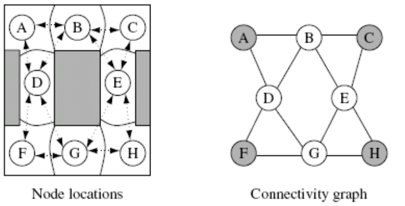


Figure2 The approximate point-in –riange(APIT)technique

E. Identifying Codes

In this technique, referred to as the identifying code construction (ID-CODE) algorithm [5], the sensor deployment is planned in such a way as to ensure that each resolvable location is covered by a unique set of sensors. The algorithm runs on a deployment region graph G=(V, E) in which vertices V represent the different regions, and the edges E represent radio connectivity between regions This is illustrated in Figure 3. The algorithm ID-CODE is a polynomial greedy heuristic that provides good solutions in practice. There also exists a robust variant of this algorithm called r-ID-CODE [5] that can provide robust identification, i.e. guaranteeing a unique set of IDs for each location, even if there is addition or deletion of up to r ID values.



Transmitters A, F, C, H provide unique IDs for all node locations

V:	A	B	C	D	E	F	G	H
ID:	A	A,C	C	A,F	C,H	F	F,H	H

Figure 3 Illustration of the ID-CODE technique showing uniquely identifiable regions

V.FINE-GRAINED NODE LOCALIZATION.

These include triangulation using distance estimates, pattern matching, and sequence decoding. Although used in the large-scale GPS, signals are not capable of providing precise distance estimates over short ranges typical of WSN because of synchronization limitations. Therefore other techniques such as radio signal strength (RSS) measurements and time difference of arrival (TDoA) must be used for distance-estimation.

Radio signal-based distance-estimation (RSS)- To a first-order approximation, mean radio signal strengths diminish with distance according to a power law. RSS-based ranging may perform much better in situations where the fading effects can be combated by diversity techniques that take advantage of separate spatio-temporally correlated signal samples.

Distance-estimation using time differences (TDOA)- A more promising technique is the combined use of ultrasound/acoustic and radio signals to estimate distances by determining the TDOA of these signals[6]. This technique is conceptually quite simple, and is illustrated in Figure4. The idea is to simultaneously transmit both the radio and acoustic signals (audible or ultrasound) and measure the times Tr and Ts of the arrival of these signals respectively at the receiver.

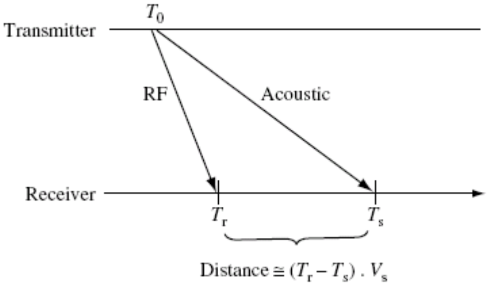


Figure 4 Ranging based on time difference of arrival

Since the speed of the radio signal is much larger than the speed of the acoustic signal, the distance is then simply estimated as (Ts-Tr). Vs, where Vs is the speed of the acoustic signal. One minor limitation of acoustic ranging is that it generally requires the nodes to be in fairly close proximity to each other (within a few meters) and preferably in line of sight. On the whole, acoustic TDOA ranging techniques can be very accurate in practical settings. For instance, it is claimed in [6] that distance can be estimated to within a few centimeters for node separations fewer than 3 meters. Of course, the tradeoff is that sensor nodes must be equipped with acoustic transceivers in addition to RF transceivers.

Triangulation using distance estimates- The location of the unknown node (x_o,y_o) can be determined based on measured distance estimates $\hat{d}_i$ to n reference nodes $\{(x_1, y_1)..(x_i , y_i)..(x_n ,y_n)\}$. This can be formulated as a least squares minimization problem. The least squares minimization problem is then to determine the (x_o,y_o) that minimizes $\sum_{i=1}^{n} (\rho_i)^2$ This problem can be solved by the use of gradient descent techniques or by iterative successive approximation techniques. An alternative is the following approach, which provides a numerical solution to an over-determined (n≥3) linear system [6].

Angle of arrival (AOA)- Another possibility for localization is the use of angular estimates instead of distance estimates. Angles can potentially be estimated by using rotating directional beacons, or by using nodes equipped with a phased array of RF or ultrasonic receivers. Angulation with ranging is a particularly powerful combination [7].

Pattern matching (RADAR)- An alternative to measuring distances or angles that is possible in some contexts is to use a pre-determined "map" of signal coverage in different locations of the environment, and use this map to determine where a particular node is located by performing pattern matching on its measurements. An example of this technique is RADAR.

RF sequence decoding (ecolocation)- The ecolocation technique [8] uses the relative ordering of received radio signal strengths for different references as the basis for localization.

VI. NETWORK-WIDE LOCALIZATION

A. Issues-

A broader problem in sensor systems is that of *network localization*, where several unknown nodes have to be localized in a network with a few reference nodes

The performance of network localization depends very much on the resources and information available within the network. There may be several ways to measure the performance of network localization.

B. Constraint-Based Approaches-

Geometric constraints can often be expressed in the form of linear matrix inequalities and linear constraints [3]. This applies radial constraints, annular constraints, angular constraints, as well as other convex constraints. Information about a set of reference nodes together with these constraints describes a feasible set of constraints for a semifinite program. By selecting an appropriate objective function for the program, the constraining rectangle, which bounds the location for each unknown node, can be determined. When using bounding rectangles, a distributed iterative solution can be used [4].

C. RSS-Based Joint Estimation-

In the joint MLE technique, first an expression is derived for the likelihood that the obtained matrix of power measurements would be received given a particular location set for all nodes; the objective is then to find the location set that maximizes this likelihood.

D. Iterative Multilateration-

The iterative multilateration technique [6] is applicable whenever inter-node distance information is available between all neighboring nodes. The algorithm is quite simple. It applies the basic triangulation technique for node localization in an iterative manner to determine the locations of all nodes. Figure5 shows an example of a network with one possible sequence in which unknown nodes can each compute their location so long as at least three of their neighbors have known or already computed locations.

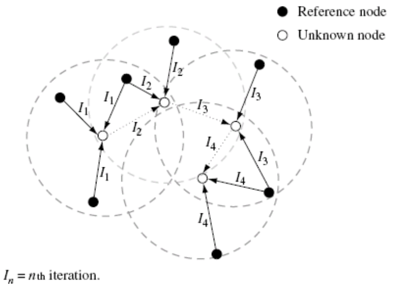


Figure 5 Illustration of sequence of iterative multilateration steps

E. Collaborative Multilateration

The key insight is to determine collaborative subgraphs within the network that contain reference and unknown nodes in a topology such that their positions and inter-node distances can be written as an over-constrained set of quadratic equations with a unique solution for the location of unknown nodes. Used in conjunction with iterative multilateration, this technique is generally useful in portions of the network where the reference node density is low.

F. Multi-Hop Distance-Estimation Approaches-

An alternative approach to network localization utilizes estimates of distances to reference nodes that may be several hops away. These distances are propagated from reference nodes to unknown nodes using a basic distance-vector technique. There are three variants of this approach:

1. DV-hop:
2. DV distance:
3. Euclidean propagation:

Once distance estimates are available from each unknown node to different reference nodes throughout the network, a triangulation technique can be employed to determine their locations.

G. Refinement-

Once a possible initial estimate for the location of unknown nodes has been determined through iterative multilateration/collaborative multilateration or the distance-vector estimation approaches, additional refinement steps can be applied. Each node continues to iterate, obtaining its neighbors location estimates and using them to calculate an updated location using triangulation. After some iteration, the position updates become small and this refinement process can be stopped.

H. Force-Calculation Approach-

It should be kept in mind that this technique may be susceptible to local minima.

I. Multi-Dimensional Scaling-

Another network localization approach utilizes a data analysis technique known as multi-dimensional scaling (MDS) [9]. It consists of the following three steps:

1. Use a distance-vector algorithm
2. Apply classical metric-
3. Take the position of reference nodes

J. Reference-Less Localization-

In some scenarios, we may encounter sensor networks that are deployed in such an *adhoc* manner, without GPS capabilities, that there are no reference nodes whatsoever. In such a case, the best that can be hoped for is to obtain the location of the network nodes in terms of relative, instead of absolute, coordinates. [10] Their algorithm is described as a progression of three scenarios with successively fewer assumptions:

1. All (and only) nodes at the boundary of the network are reference nodes.
2. Nodes at the boundary are aware that they are at the boundary, but are not reference nodes.
3. There are no reference nodes in the network, and no nodes are aware that they are at the boundary. Figure 6 gives example of final solution.

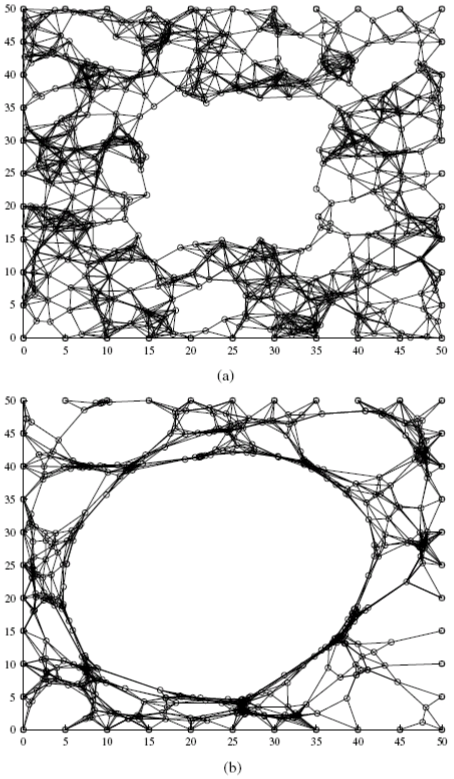


Figure 6 An illustration of the reference-less network localization technique assume boundary node locations are known:(a) original map (b) obtained relative map

VII. THEORETICAL ANALYSIS OF LOCALIZATION TECHNIQUES

A. Cram´Er–Rao Lower Bound

One theoretical tool of utility in analyzing limitations on the performance of localization techniques is the use of the Cramér–Rao bound. The Cramér–Rao bound (CRB) is a well-known lower bound on the error variance of any unbiased estimator, and is defined as the inverse of the Fisher information matrix .The CRB can be derived for different assumptions about the localization technique. The CRB has been used to investigate error performance of K-level quantized RSSI-based localization.

B. Unique Network Localization

There is a strong connection between the problem of unique network localization and a mathematical subject known as rigidity theory [11]. The key result concerning the conditions for a network to be unique localizable is the following:

Theorem

A network N *is uniquely localizable if and only if the weighted grounded graph* G'_N *corresponding to it is globally rigid.*

There are two terms here that need to be explained – weighted grounded graph and global rigidity. The *weighted grounded graph* G'_N is constructed from the graph described by network N by adding additional edges between all pairs of reference nodes, labeled with the distance between them. We shall give an intuitive definition of global rigidity. Consider a configuration graph of points in general position on the plane, with edges connecting some of them to represent distance constraints. Is there another configuration consisting of different points on the plane that preserves all the distance constraints on the edges? If there is not, the configuration graph is said to be globally rigid in the plane. Figure7 gives examples of non-globally rigid and globally rigid configuration graphs.

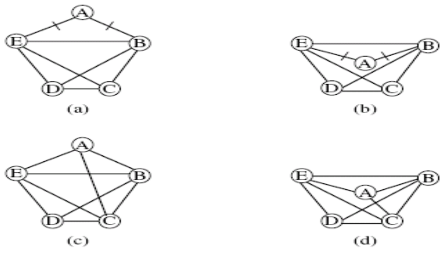


Figure7 Example of configuration graphs that are not globally rigid ((a)(b)) and that are globally rigid((c)(d))

VIII. CONCLUSION

Determining the geographic location of nodes in a sensor network is essential for many aspects of system operation: data stamping, tracking, signal processing, querying, topology control, clustering, and routing. It is important to develop algorithms for scenarios in which only some nodes have known locations. The design space of localization algorithms is quite large.

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