Introduction

- Wireless ad hoc sensor networks are being developed to collect data across the area of deployment.
- It is necessary to identify the position of each sensor to
  - stamp the collected data
  - facilitate communication protocols.
Introduction

- Multilateration
  - Multilateration, is the process of locating an object by accurately computing the time difference of arrival (TDOA) of a signal emitted from the object to three or more receivers.

- Trilateration or Multilateration are based on
  - received signal strength indicator (RSSI)
  - the time of arrival (TOA)
  - the time difference of arrival (TDoA)
  - angle of arrival (AoA)

- Standing at \( B \), you want to know your location relative to the reference points \( P_1 \), \( P_2 \), and \( P_3 \) on a 2D plane.
  - Measuring \( r_1 \) narrows your position down to a circle.
  - Next, measuring \( r_2 \) narrows it down to two points, \( A \) and \( B \).
  - A third measurement, \( r_3 \), gives your coordinates at \( B \).
Introduction

• Situations that most existing sensor positioning methods fail to perform well.
  – when the topology of a sensor network is anisotropic (directionally dependent).
  – complex terrain

Solution

• The Distributed sensor positioning method with an estimation–comparison–correction paradigm address these conditions
Solution

- Multidimensional scaling (MDS) technique is applied to recovering a series of local maps for adjacent sensors in two- (or three-) dimensional space.

- These maps are then stitched together to form a global map marking all sensors’ locations.

- Then, the estimated positions of anchor sensors are compared with their physical positions.
Introduction

• The method avoids measurement errors caused by
  – anisotropic network topology
  – complex terrain

Background Information

• A general setup of a wireless sensor network consists of a large number of sensors randomly and densely deployed in a certain area.

Background Information

• Each sensor usually is capable of sensing, processing data at a small scale, and communicating through unidirectional radio signal.
**Background Information**

- Omni direction radio signal become weaker with a distance
- only sensors within a certain range can communicate with each other.
- This range is called hop distance R.

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**Background Information**

- Wireless sensor networks significantly differ from classical networks on their
  - strict limitations on energy consumption
  - the simplicity of the processing power of nodes

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**Physical Positions Of Sensors**

- Determining the physical positions of sensors is a fundamental and crucial problem in wireless ad hoc sensor network operation for several important reasons.
In order to use the data collected by sensors, it is often necessary to have their position information stamped. For example, in order to detect and track objects.

Many communication protocols of sensor networks are built on the knowledge of the geographic positions of sensors.

In most cases, sensors are deployed without their position information known in advance.
Physical Positions Of Sensors

• Global Positioning System (GPS) installed in all sensors.

Physical Positions Of Sensors

• It is not practical to use GPS due to
  – its high power consumption
  – expensive price
  – line-of-sight conditions.

Physical Positions Of Sensors

• Use of anchor nodes
Challenges Of The Sensor Positioning Problem

- In real applications.
- The conditions that most existing sensor positioning methods fail to perform well are
  - the anisotropic topology of the sensor networks
  - complex terrain where the sensor networks are deployed.

Estimation-Comparison-Correction

- A series of local maps of adjacent sensors along the route from an anchor (starting anchor) to another anchor (ending anchor) are computed.

Multi Dimensional Technique

- MDS has been successfully used to capture the intercorrelation of high dimensional data at low dimension in social science, to compute the local maps
Multidimensional Scaling

- MDS is a data analysis technique that display the structure of distance like data as a geometrical picture.

Multidimensional Scaling

- MDS has now become a general data analysis technique used in a wide variety of fields.
- MDS pictures the structure of a set of objects from data that approximate the distances between pairs of the objects.

Multidimensional Scaling

- These local maps are then pieced together to get the approximation of the physical positions of the sensor nodes.
Multidimensional Scaling

• Since the position information of the starting anchor is known, with the stitched maps, the position of the ending anchor can be estimated, which may be different from the true position of the ending anchor.

Background Information

• When aligning the calculated position and the true position of ending anchor, the positions of sensors in the stitched maps will approximate their true positions effectively.

Background Information

• The method is also efficient in eliminating cumulative measurement errors.
Efforts To Solve The Sensor Positioning Problem

- There have been many efforts to solve the sensor positioning problem.
- They mainly fall into one of the following four classes or the combinations of them.

Methods Improve The Accuracy

- The first class of methods improve the accuracy of distance estimation with different signal techniques.
  - The Received signal Strength Indicator (RSSI) technique was employed to measure the power of the signal at the receiver.
  - Relatively low accuracy is achieved in this way.
  - It is widely used, because of its simplicity.

- Time of Arrival (ToA)
- Time Difference of Arrival (TDoA) are used to reduce the errors of range estimation.
Methods Improve The Accuracy

• These methods require each sensor node being equipped with a CPU with powerful computation capability.

Methods Improve The Accuracy

• Recently Angle of Arrival (AoA) used to measure the positions of sensors.

• But AoA sensing requires each sensor node installed with an antenna or ultrasound receivers.

Methods Improve The Accuracy

• The second class of positioning methods relies on a large amount of sensor nodes with positions known densely distributed in a sensor network.
Methods Improve The Accuracy

• These nodes with positions known, which are also named as beacons or anchor nodes, are arranged in a grid across the network to estimate other nodes' positions nearby them.

Methods Improve The Accuracy

• The third class of methods employ distance vector exchange to find the distances from the non-anchor nodes to the anchor nodes.

Distance Vector

• A number of different approaches for finding routes between networks are possible.
Distance Vector

• One useful way of categorizing these approaches is on the basis of the type of information the gateways need to exchange in order to be able to find routes.

Distance Vector

• Distance vector algorithms are based on the exchange of only a small amount of information.

Distance Vector

• Each entity (gateway or host) that participates in the routing protocol is assumed to keep information about all of the destinations within the system.
Distance Vector

- Routing protocols can be classified as
- Proactive
- Reactive

Based on these distances, each node can estimate its position by performing a trilateration or multilateration.

Methods Improve The Accuracy

- The performance of the algorithms is deteriorated by range estimation errors and inaccurate distance measures.
Methods Improve The Accuracy

- This is caused by
  - complex terrain
  - anisotropic topology

Methods Improve The Accuracy

- Figure
- A and B are two anchors, A may estimate hop distance with the distance of AB and hop count in the route from A to B.
Methods Improve The Accuracy

• If A and B estimate their distances to C with the estimated hop distance, the estimated distances will be increased a lot by error.

Methods Improve The Accuracy

• The routes between a pair of sensors are detoured severely by the buildings in the square area, and the estimated distances are increased significantly.
Methods Improve The Accuracy

- Example

Here sensors are deployed on a square area with deep grass or bush on the left part and clear ground on the right.
Methods Improve The Accuracy

• The complexity of and terrain leads to different signal reduction factors and hop distances in the field.

Challenges

• Since a large number (up to thousands) of sensors are usually used when they are densely deployed across a given area.

Challenges

• Goal is to achieve good position estimation as well as keep the hardware design of sensors simple and cheap.
Challenges
• In many circumstances it is impossible to get a large number of anchor nodes deployed densely and uniformly to assist position estimation of nonanchor nodes.

Challenges
• Thus, it is desirable to design a sensor positioning method that is able to generate accurate position estimation with as few anchors as possible.

Challenges
• Most of the previous methods estimate an average hop distance and broadcast it to the whole network.
Challenges

• In many cases, sensors may be deployed on an area with anisotropic vegetation and terrain condition.

Challenges

• Thus, sensors at different portions of the area can have different hop distances, and a uniform hop distance in calculation will lead to errors and serious cumulative errors.

Calculating Relative Positions with MDS

• MDS a technique widely used for the analysis of dissimilarity of data on a set of objects, can disclose the structure in the data.
Calculating Relative Positions with MDS

- MDS, a data-analytic approach to discover the dimensions that motivate the judgments of distance and model data in geometric space.

The main advantage in using the MDS for position estimation is that it can always generate high accurate position estimation even based on limited and error-prone distance information.

There are several varieties of MDS. We focus on classical MDS and the iterative optimization of MDS, the basic idea of which is to assume that the dissimilarity of data are distances and then deduce their coordinates.
Classical Multidimensional Scaling

• We will use

\[ T = [t_{ij}]_{2 \times n} \]

Where \( T \) record the physical positions of the \( n \) sensors deployed, each in two-dimensional space.

• The term \( d_{ij}(T) \) represents the Euclidean distance between sensor \( i \) and \( j \) based on their positions in \( T \), and we have

\[ d_{ij} = \left( \sum_{x=1}^{2} (x_i - x_j)^2 \right)^{1/2} \]

• The collected distance between node \( i \) and \( j \) is denoted as \( \Delta_{ij} \).

• If we ignore the errors in distance measurement then

\[ \Delta_{ij} = d_{ij}(T) \]
Classical Multidimensional Scaling

The expression

\[ X = [x_{ij}]_{2 \times n} \]

denotes the estimated positions of the set of \( n \) sensor nodes in two-dimensional (2D) space.

Classical Multidimensional Scaling

- If all pair wise distances of sensors in \( T \) are collected, we can use the classical multidimensional scaling algorithm to estimate the positions of sensors as

Iterative Multidimensional Scaling

- In many situation, the distances between some pairs of sensors in the local area are not available.
- When this happens, the iterative MDS is employed to compute the relative coordinates of adjacent sensors.
Iterative Multidimensional Scaling

- It is an iterative algorithm based on multivariate optimization for sensor position estimation in 2D space.

Since only a portion of the pairwise distances are available, $\Delta_{ij}$ is undefined for some $i, j$.

In order to assist computation, we define weights $w_{ij}$ with value 1 if $\Delta_{ij}$ is known and 0 if $\Delta_{ij}$ is unknown and assume

$$\delta_{ij} = d_{ij}(T)$$
Distributed Sensor Positioning Method Based on MDS

- In this sensor positioning method, the above MDS techniques are used in a distributed manner by estimating a local map for each group of adjacent sensors, and then these maps are stitched together.

Hop Distance and Ranging Estimation

- Here we employ the widely used distance measurement model of received signal strength indication (RSSI).

- Nodes within one hop distance can directly communicate with each other, while nodes that are in more than one hop away relay messages through some medium nodes in hop-by-hop fashion.
Hop Distance and Ranging Estimation

- The power of the radio signal becomes weaker exponentially with distance.

- This property enables the receiver to estimate the distance to the sender by measuring the weakening of the radio signal strength from the sender to the receiver.

- For example, there are four sensor nodes A, B, C, and D in Figure.
  - Hop distance is $r_h$.
  - The distance between A and D, $r_{ad}$, can be inferred from A's signal strength at the position of D.
Aligning Relative Positions to Physical Positions

Hop Distance and Ranging Estimation
- It is necessary to point out that some other distance measure approaches, such as TOA, TDOA, AoA, and ultrasound, can also be applied here.

Hop Distance and Ranging Estimation
- They even generate more accurate distance measure than RSSI, but they need very complex hardware equipped in each sensor.
Aligning Relative Positions to Physical Positions

- After the pairwise distances of a group of adjacent sensors are estimated, their relative positions (or a local map) can be calculated with the MDS techniques.

Aligning Relative Positions to Physical Positions

- Since we hope to compute the physical positions of all sensors with our distributed positioning method.
- It is necessary to align the relative positions to physical positions with the aid of sensors with known positions.

Aligning Relative Positions to Physical Positions

- At least three sensors’ physical positions are required in order to identify the physical positions of remaining nodes in the group in the 2D case.
Aligning Relative Positions to Physical Positions

- Thus, each group of adjacent sensors must contain at least three nodes with physical positions known, which can be anchors or nodes with physical positions calculated previously.

Aligning Relative Positions to Physical Positions

- The alignment usually includes shift, rotation, and reflection of coordinates.

Distributed Physical Position Estimation

- An anchor node called starting anchor initializes flooding to the whole network.
Distributed Physical Position Estimation

• When other anchor nodes, called ending anchors, get the flooding message, they pass their positions back to the starting anchor along with the reverse routes from starting anchor to each of them.

Distributed Physical Position Estimation

• Then the starting anchor knows the positions of ending anchors and routes to each of them.

Distributed Physical Position Estimation

• Starting anchor estimates the positions of those sensors that are on these routes and one hop away from it.
Distributed Physical Position Estimation

• A is the starting anchor, D and H are the ending anchors.
• Anchor A knows the positions of D and H as well as the routes to them, which are (A, B, C, D) and (A, E, F, G, H), respectively.

Distributed Physical Position Estimation

• Anchor A estimates that the position of B is B’ on dashed line AD and the position of E is E’ on dashed line AH.
Distributed Physical Position Estimation

• Anchor A also estimates the average hop distances in the direction of AD and AH, respectively.

Distributed Physical Position Estimation

• With the collection of pairwise distances among neighboring nodes by RSSI sensing, MDS can be performed to calculate the local map (or the relative positions) for neighboring sensor nodes.

Distributed Physical Position Estimation

• The relative positions of neighboring nodes A, B, E, J, K are calculated by A.
Distributed Physical Position Estimation

• Through aligning the relative positions of A, B, E with their physical positions, the physical positions of J, K can be calculated as well.

Distributed Physical Position Estimation

• In the same way, localized mapping and alignment are performed for sensor nodes along a route from the starting anchor to an ending anchor.
• Figure 2.24 illustrates the procedure of propagated position estimation from starting anchor to ending anchor.
In Figure 2.24, A is the starting anchor and D is the ending anchor. The remaining nodes are along the route of flooding from A to D, and each local map is represented with a dash ellipse.

Map i contains adjacent sensors E, F, G, H, K. Since the physical positions of E, F, G are calculated previously, the physical positions of H, K can be computed with the above MDS and alignment techniques.
Distributed Physical Position Estimation

• Then H, K, I, J, and G are adjacent sensors and build map j to further estimate I and J's positions.

Distributed Physical Position Estimation

• Figure 2.25 illustrates four adjacent sensors A, B, C, and D; r is the hop distance; A, B, and C are nodes with positions known; D collects the position of A, B, and C, and then calculates their pairwise distances; D also has its distances to A, B, C, respectively.

Distributed Physical Position Estimation

• Thus, D can perform a classical MDS to compute the local map (or relative positions of the four sensors).
Distributed Physical Position Estimation

- Figure 2.26 illustrates an example of six adjacent sensors A, B, C, D, E, and F; \( r \) is the hop distance; sensors A, B, C, and D know their positions, and sensors E and F do not know their positions; E collects the position of A, B and its distances to them.

Then E relays this information to F; and F collects the positions of C, D and its distances to them.

Thus, F can compute the pairwise distances of the six sensors except the distances of AF, BF, CE, and DE.

Term F can perform an iterative MDS to compute the local map (or the relative positions of the six sensors).

Then, positions of all nodes around a route from a starting anchor to an ending anchor and the ending anchor itself can be estimated.
Distributed Physical Position Estimation

- For example, in Figure 2.23, the estimated position of nodes E, F, G are E', F', G', respectively.
- With the physical position of G known in advance, we can compare G' and G and align them if they are not equal (rotate <G' AG with A as center and then scale AG' to AG).

Distributed Physical Position Estimation

- We can also apply the same alignment to the coordinates of all sensors along the route, such as E' and F'.
Distributed Physical Position Estimation

• In general, the positions of E’ and F’ are effectively corrected and approximated to their true positions, respectively.

Distributed Physical Position Estimation

• The above position estimation procedures are executed iteratively on a route from a starting anchor to an ending anchor until estimated positions converge.

Centralized Sensor Positioning Method Based on MDS

• Multidimensional scaling can also be used to estimate all sensors’ relative positions through one centralized computation.
Centralized Sensor Positioning Method Based on MDS

- In order to collect some of pairwise distances among sensors, we select a number of source sensors, and they initialize flooding to the whole network to estimate some of the pairwise distances.

Centralized Sensor Positioning Method Based on MDS

- These estimated distances are then transmitted to a computer or sensor for centralized computation of MDS.

Centralized Sensor Positioning Method Based on MDS

- The details on flooding and pairwise distances collection is presented next.
Centralized Sensor Positioning Method Based on MDS

- Network of sensors are randomly, densely distributed.
- They are sufficiently connected in a general ad hoc sensor network model.

Centralized Sensor Positioning Method Based on MDS

- The key operation in pairwise distance collection is to select several sensor nodes flooding across the network.

Centralized Sensor Positioning Method Based on MDS

- An anchor node is selected as source sensor to initialize a broadcast containing its ID, position, and hop count equal to 0.
Centralized Sensor Positioning Method Based on MDS

- Each of its one-hop neighbors hears the broadcast, appends its ID to the message, increases the hop count by 1, and then rebroadcasts it.

Centralized Sensor Positioning Method Based on MDS

- Every other node that hears the broadcast but did not hear the previous broadcasts with lower hop count will append its ID, increase the hop count by 1, and then rebroadcast.

Centralized Sensor Positioning Method Based on MDS

- The process continues until all nodes in the sensor network get the message broadcasted by the original source node.
Centralized Sensor Positioning Method Based on MDS

- Each node that is far away from the source node usually keeps a route from source node to it.

Centralized Sensor Positioning Method Based on MDS

- An example broadcast is illustrated in Figure 2.27, where node S initializes a flooding and the average hop distance is r. Each route found is indicated with connected arrow lines.

Figure 2.27: Routes of a flooding initialized by node S.
Centralized Sensor Positioning Method Based on MDS

- Nodes A, B, C, D, E, F, G each keep the corresponding route information from node S to them, respectively.

- The distance of any pair of nodes on one of the routes can be calculated by multiplying the average hop distance by the number of hop counts between them on the route.

- Usually, a source node's broadcast only collects the pairwise distances of nodes for which the route information is available.
Centralized Sensor Positioning Method Based on MDS

• When another anchor node hears the broadcast, it uses the information in the received message to induce the average hop distance.

• The anchor node is then selected as a new source node, and it initializes another broadcast later to collect more pairwise distances as well as publish the average hop distance.

• Similarly, we can select some other nodes as source nodes to broadcast.

• For n sensors in a sensor network, there are n(n — 1)/2 pairwise distances in total.
Centralized Sensor Positioning Method Based on MDS

- Our experimental results indicate that a source node flooding usually collects 3% to 8% of all pairwise distances depending on the relative position of the source node in the network, the connection degree of nodes, and hop distance.

Centralized Sensor Positioning Method Based on MDS

- The above iterative MDS will generate position estimation with various accuracies depending on the percentage of the pairwise distances collected to all pairwise distances.

Centralized Sensor Positioning Method Based on MDS

- Usually, more than 10% pairwise distance is needed for a good position estimation.
- Thus, a certain number of source nodes (anchor nodes or nonanchor nodes) should be selected to initialize flooding.
Centralized Sensor Positioning Method Based on MDS

• However, the total number of pairwise distances collected does not increase linearly with the number of source nodes, since there are a lot of overlaps among the sets of collected flooding routes by different source nodes.

Centralized Sensor Positioning Method Based on MDS

• We hope to initialize with as less source sensors flooding as possible and collect as many pairwise distances as possible.

Centralized Sensor Positioning Method Based on MDS

• This requires that broadcast from each source sensor can collect relatively more pairwise distances and the overlap among sets of pairwise distances collected by every source node's broadcast should be small.
Centralized Sensor Positioning Method Based on MDS

- An approximated topology of a sensor network with 37 sensor nodes is plotted in Figure 2.30.

- Node S initializes the broadcast and the circle centered with S represents the range of signal.

- Some routes marked by arrow lines are selected to connect 16 nodes, while other routes are omitted.

- These selected routes contain relatively more nodes than other routes.
Centralized Sensor Positioning Method Based on MDS

• Based on the route information in nodes A, B, C, D, E, F, G, we can induce 34 pairwise distances.

Centralized Sensor Positioning Method Based on MDS

• Based on the grid model, we have the following observations:
  1. A flooding initialized by a source node located at the border of the network usually collects more pairwise distance than that of a source node located at the center of the network.
  2. Flooding initialized by source nodes far away from each other tends to generate pairwise distance sets with less overlap.