Localization and positioning

Describes the (symbolic location) & (numeric position) of wireless sensor node.

→ Properties of localization methods and possibilities for a node to determine information about its position are discussed.

This chapter provides a principal design tradeoff for positioning and gain an appreciation for overhead involved in obtaining the information.

Properties of localization and positioning procedures

Providing location information to a node has a number of facets. The important properties are:

(i) **Physical position vs symbolic location**:

Does the system provide data about physical position of a node (in some numeric coordinate system) or does a node learn about symbolic location (eg: office 123 in building 4)

(ii) **Absolute versus relative coordinates** (Abs. coordinate system valid for all objects and relative system differ for any object)

Absolute coordinate system is valid for all objects. for ex: positions in the Universal Transverse Mercator (UTM) coordinates form an absolute coordinate system for any place on earth. Relative coordinates differ for any located object or a set of objects. a WSN where nodes have coordinates that are correct w.r.t each other but have no relationship to absolute coordinates.

→ (To provide absolute coordinates, few anchors are necessary) The anchors are nodes that know their own position in the absolute coordinate system. Anchors can rotate, translate and possibly scale a relative coordinate system so that it coincides with the absolute coordinate system. Anchors are also known as beacons, landmarks.

Localized vs centralized computation

Localized computation provides scaling and efficiency considerations (both computational and commn overhead). It also provides privacy to participant not to reveal its position to central entity.

Accuracy and precision: Positioning accuracy is the largest distance betn estimated & true position of an entity. Precision is the ratio with which a given accuracy is reached, averaged over many repeated attempts to determine a position. Ex: A system can provide 20cm accuracy with 95% precision (accuracy → value, Precision → Percentage)

Scale:

system can be intended for different scales - indoor deployment, size of room or building or outdoor deployment. The two important metrics are: the area the system can cover per unit of infrastructure and the number of locatable objects per unit of infrastructure per unit time interval. (object in a grid)

Limitations:

For some positioning tech. there are inherent deployment limitations. GPS don't work for indoors, other systems have limited ranges.

Costs: (time, space, energy, capital)

Positioning system can cause costs in time (infrastructure installation, administration), space (device size, space for infrastructure) energy (during operation) and capital (price of a node, infrastructure installation).

Possible approaches < Proximity, geometric Prop. (Triangulat^n & trilaterat^n), Scene analysis

The main approaches to determine a node's position are using information about a node's neighborhood (proximity-based approach), exploiting geometric properties of a given scenario (triangulation and trilateration) and trying to analyze characteristic properties of the position of a node in comparision with premeasured properties (Scene analysis).

Proximity: (closeness or vicinity) (A ~~distance~~ connectivity measure bet^n nodes)

→ This is used to decide whether a node wants to determine its position or location is in the proximity of an anchor.

→ Proximity based systems can be quite sophisticated and can even be used for approximate positioning when a node can analyze proximity informat^n of several overlapping anchors.

→ They can be relatively robust to uncertainties of wireless channel deciding whether a node is in proximity of another node is equivalent to deciding connectivity, which can happen on relatively long time scales, averaging out short-term fluctuations.

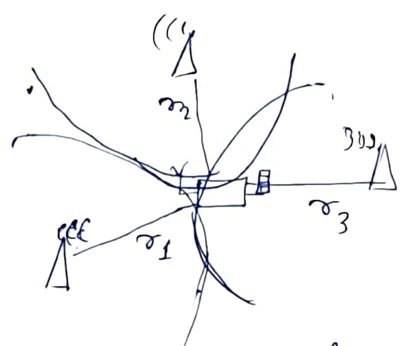
Trilateration and triangulation

Lateration versus angulation.

In addition to connectivity / proximity information, the commn. betn. two nodes allows to extract information about their geometric relationship. For example estimation of distance betn. two nodes or the angle in ~~triangle~~ triangle. Using geometry this information can be used to derive information about node positions.

→ When distance betn. entities used the approach is called lateration & when angle between nodes used this approach is called angulation.

→ For lateration in a plane, for a node it have (precise distance measurements) to three noncolinear anchors. Using distances and anchor positions, the node's position is the intersection of three circles around the anchors.



→ The issue with this that distance measurement are never perfect and intersection of these three circles will not result in a single point. To overcome this distance measurement from more than 3 anchors can be used, resulting in (multilateration problem).

→ Angulation exploits the fact that in a triangle once the length of two ~~remaining~~ sides & two angles are known the position of third point is known as intersection of the two remaining sides of the triangle.

Determining distances: (To use multi-lateration, distance estimates to anchor nodes are required). The characteristics of wireless commn. are particularly determined by the distance betn. sender and receiver, if these characteristics can be measured at receiver they can serve as an estimator of distance. The important c/cs are Received Signal Strength indicator (RSSI), Time of Arrival (TOA), Time Difference of Arrival (TDOA)

RSSI: Assuming transmission power P_{tx}, Path loss coefficient α, and known path loss model, the received signal strength P_{rcvd} is used to solve for distance d in path loss eqn. as.

$$P_{recvd} = \frac{c\,P_{tx}}{d^{\alpha}} \Rightarrow d = \sqrt[\alpha]{\frac{c\,P_{tx}}{P_{recvd}}}$$

→ (As RSSI is a ranging technique), it is necessary to accept and deal with considerable ranging errors (As RSSI values are not constant but heavily oscillate even when sender & receiver don't move.

Time of arrival (TOA): It is often called as Time of flight (ToF), which exploits the relationship betn distance & transmission time when the propagation speed is known.

→ Assuming both sender & receiver know the time of transmission (start of ultrasound pulse), the time of arrival of this transmission at receiver is used to compute propagation time and thus distance.

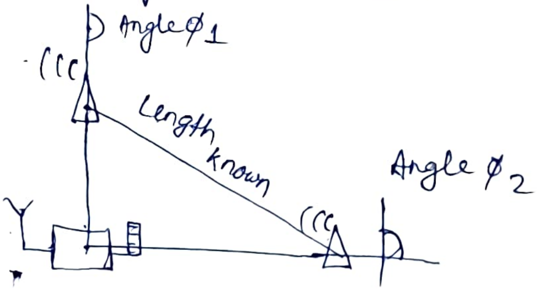
→ one disadvantage of sound is the propagation (speed depends on external factors such as temperature or humidity) - careful calibration is necessary but not obvious.

Time difference of arrival: This method utilizes implicit synchronization by providing directly the start of transmission information to the receiver.

→ This is done if two transmission mediums of very different propagation speeds are used i.e radio waves propagating at speed of light & ultrasound with diff. speed. Hence when sender starts an ultrasound and radio transmission simultaneously, the receiver use the arrival of radio transmission to start measuring the time of ultrasound transmission arrival and in this way avoids propagation time of radio commn. Hence, it produces a more accurate distance measurement but has disadvantage that it uses two types of sender & receiver at each node.

Determining angles:

Alternative to measuring distance betn nodes angles can be measured. This angle can be either the angle of connecting line betn anchor & position unaware node to a given directn (0° north). It can be the angle betn two such connecting lines if no reference direction is commonly known to all nodes.



Scene analysis.

Most evident form of it is to analyze pictures taken by a camera and to try to derive the position from this picture. This requires more computations and not suitable for sensor nodes

→ Apart from visual pictures, other measurable c/cs "fingerprints" of a given location can be used for scene analysis.

→ Scene analysis is interesting for systems that have dedicated deployment phase and where offline measurement are acceptable. This is not always the case for WSNs. Hence, not the main technique to pay attention.

Mathematical basics for the lateration problem:

Since multilateration is one of the most popular techniques for positioning applied in WSNs

soln. with three anchors & correct distance values

Assuming 3 anchors with known positions (x_i, y_i), $i=1,..3$, a node at unknown position (x_u, y_u) and perfect distance values r_i, $i=1,..3$. The set of three eqn (s) are

$$(x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2 \quad \text{for } i=1,..3$$

To solve the set of eqn(s), it is more convenient to write it as a set of linear eqns) in x_u and y_u. To remove quadratic terms x_u^2 & y_u^2 we subtract third eqn from previous two eqns).

$$(x_1 - x_u)^2 - (x_3 - x_u)^2 + (y_1 - y_u)^2 - (y_3 - y_u)^2 = r_1^2 - r_3^2$$

$$(x_2 - x_u)^2 - (x_3 - x_u)^2 + (y_2 - y_u)^2 - (y_3 - y_u)^2 = r_2^2 - r_3^2$$

Rearranging

$$2(x_3 - x_1) \cdot x_u + 2(y_3 - y_1) \cdot y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$

$$2(x_3 - x_2) \cdot x_u + 2(y_3 - y_2) \cdot y_u = (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$$

which can be easily rewritten as a linear matrix eqn.

$$2\begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\ (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) \end{bmatrix}$$

Ex: Position determination $(x_1, y_1) = (2,1)$, $(x_2, y_2) = (5,4)$ & $(x_3, y_3) = (8,2)$ with the distances betn. anchors and node of unknown position $r_1 = \sqrt{10}$, $r_2 = 2$, $r_3 = 3$

$$2\begin{bmatrix} 6 & 1 \\ 3 & -2 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} 64 \\ 22 \end{bmatrix}$$

results in $x_u = 5$ & $y_u = 2$ as the position of unknown node

Solving with distance errors.

The main challenge for triangulation is when distance r_i is associated with error ϵ_i, then solving through previous eqns would not give correct values for unknown position (x_u, y_u). Then the soln. is to use more than 3 anchors and redundant distant measurements to account for the error in each individual measurement. Hence in matrix form

$$2\begin{bmatrix} x_n - x_1 & y_n - y_1 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix}\begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_n^2) - (x_1^2 - x_n^2) - (y_1^2 - y_n^2) \\ \vdots \\ (r_{n-1}^2 - r_n^2) - (x_{n-1}^2 - x_n^2) - (y_{n-1}^2 - y_n^2) \end{bmatrix}$$

The soln. is the pair (x_u, y_u) that minimizes $\|AX - b\|_2$ where A is the $(n-1)\times 2$ matrix, $\underset{2\times 1}{X} = (x_u, y_u)$ is the vector describing position, and b is the right side $n-1 \times 1$ vector. We have to minimize the objective $\|AX - b\|_2^2$, hence.

$$\|AX - b\|_2^2 = (AX-b)^T(AX-b) = X^TA^TAX - 2X^TA^Tb + b^Tb$$

$$\frac{d}{dx}\left[X^TA^TAX - 2X^TA^Tb + b^Tb\right] = 0$$

$$\Rightarrow 2A^TAX - 2A^Tb = 0 \Rightarrow A^TAX = A^Tb$$

Position with imprecise information.

Assuming for three anchors; incorrect position estimation $\tilde{r}_1 = 5$, $\tilde{r}_2 = 1$, and $\tilde{r}_3 = 4$. Solving this for position using 3 anchor based method provide incorrect position $(5.2, 4.8)$ with distance of $\sqrt{(5.2-5)^2 + (4.2-2)^2} \approx 2.2$ betn. estimated and correct position.

Adding additional anchors at $(x_4, y_4) = (3,1)$, $(x_5, y_5) = (7,5)$, $(x_6, y_6) = (2,8)$ and $(x_7, y_7) = (4,6)$ with distance estimates $\tilde{r}_4 = 2$, $\tilde{r}_5 = 3$, $\tilde{r}_6 = 7$, respectively.

The matrix A and b are:

$$A = \begin{bmatrix} 2 & 5 \\ -1 & 2 \\ -4 & 4 \\ 1 & 5 \\ -3 & 1 \\ 2 & -2 \end{bmatrix}, \quad b = \begin{bmatrix} 56 \\ -4 \\ -16 \\ 30 \\ -29 \\ 17 \end{bmatrix}$$

Solving $A^TAx = A^Tb$ for x provides $x = (5.5, 2.7)$, which results (4) in a distance error of $\sqrt{(5.5-5)^2 + (2.7-2)^2} \approx 0.86$. Hence, the estimate is improved.

Single-hop localization:

Using the distance/range or angle measurements a number of positioning or locationing systems are developed. Here, in this section focus on systems where a node with unknown position can directly communicate with anchors - if anchors are used.

(i) Active Badge: This is first system designed & built for locating simple, portable devices - badges - within a building. It uses diffused infrared as transmission medium. A badge periodically send globally unique identifier via infrared to receiver, at least one of which is installed in every room. The mapping of identifiers to receivers (rooms) is stored in a central server, which can be queried for the location of a given badge.

- uses concept of TDoA, i.e time diff (arrival) betn ultrasound & radio pulse.

(ii) Active office: Target is to positioning indoor devices. Here ultrasound is used with receivers placed at a known position, mounted in array at the ceiling of a room. The devices for which the position is to be determined act as ultrasound senders.

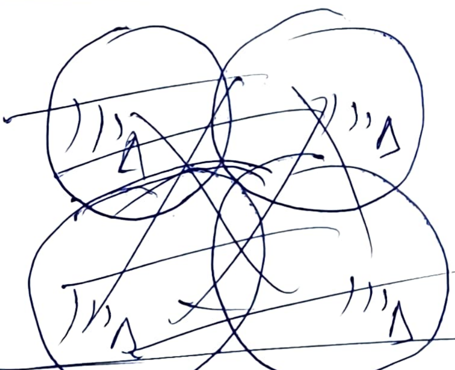
First the central controller sends radio message to device's address whose position is to be determined. After receiving the radio message device sends a short ultrasound pulse. This pulse is received by the receiver array that measures time of arrival and computes difference betn time of arrival of ultrasound pulse and time of radio pulse. Using these time, a distance estimate is computed for every receiver and the multilateration problem is solved (on central controller), and compute the position estimate for mobile ~~nodes~~ devices. The sending of radio pulse repeated after every 200 ms, allowing the devices to sleep most of time.

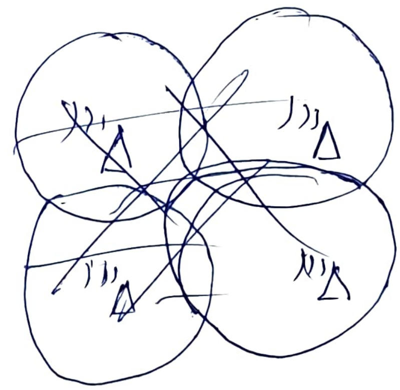
The system also compensates for imprecise distance estimates by discarding outliers and provides good accuracy.

(iii) <u>RADAR</u> : It is also used for indoor computation of position estimates. It uses scene analysis techniques, computing the received signal characteristics for multiple anchors with premeasured and stored characteristic values. Both the anchors and mobile devices can be used to send signal, which is then measured by counterpart devices. As this is an intriguing technique, the necessary offline deployment phase for measuring 'signal landscape' cannot always be accomodated in practical systems.

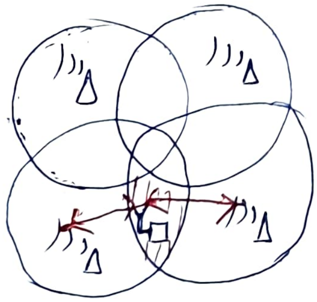
<u>Cricket</u> : (Not centralized like previous three)
In Active Bridge a active office systems the infrastructure determines the device positions. However, considering privacy issues the device can also compute their own positions & locations. Cricket system is an example of such system. In this system anchors spread on a building to provide combined radio wave & ultrasound pulses to provide TDOA measurement. From this information symbolic location information within the building is extracted.

<u>Overlapping connectivity</u> :





<u>overlapping connectivity</u> :

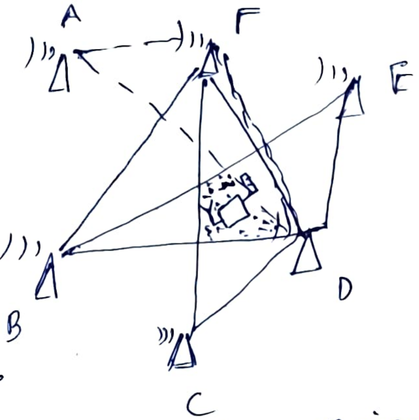


This is an outdoor positioning system that operates without any numeric range measurement. It tries to use only the observation of connectivity to a set of anchors to determine node's position. Here, the anchor's tx^n is received within a circular area of known radius. Once a node receives this from all anchors with in the node's reach, it determines the intersection of circles around the anchors.

The estimated position is the average (center) of the received anchor's positions. In this system, the achievable absolute accuracy depends on the number of anchors. More anchors allow a fine grained resolution of the area.

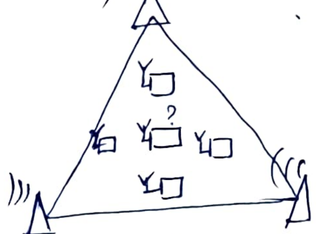
Approximate point in triangle:

Here the idea is to decide whether a node is within or outside of a triangle formed by any three anchors. Using this informatn. a node can intersect the triangles and estimate its own position, similar to intersection of circles.

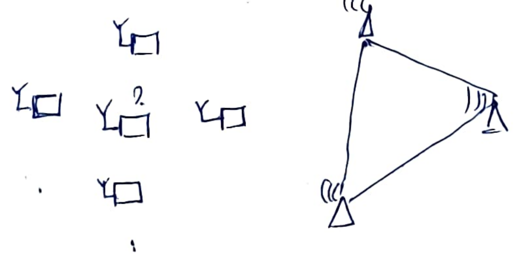


→ From figure the node has detected that it is inside triangles BDF, BDE, and CDF and also outside triangle ADF (ABF, AFC) Hence, it can estimate its position in the doted area (for ex: center of gravity of area).

→ To check a node inside the triangle, this is ~~done~~ checked through node movement. For a node, there is enquery about all its neighbors distance to given three anchors. If for all neighbors, there is atleast one corner such that the neighbor is closer to the corner than the enquiring node, it is assumed that the node is inside triangle, else outside.



(inside)



(outside)

Using angle of arrival:
(Directional antennas used narrow, rotating beams, the nodes measure time of arrival of each beam; compute diff. betn. consecutive signals) : this time allows angle computatn.

The angular informatn. in sensor n/work is obtained through anchor nodes that use narrow, rotating beams with constant rotation speed known to all nodes. Nodes then measure the time of arrival of each beam. Compute diff. betn. two consecutive signals. determine the angle α, β, and γ. The main challenge is to ensure narrow beam ($<15^\circ$) so that nodes have clear triggering point for time measurements & to handle effects of multipath propagation.

Positioning in multihop environments:

Previous assumption is that a node is in direct contact with atleast three anchor nodes, which is not always true. Therefore, a sufficiently connected graph with known edge length is used to reconstruct its embedding in the plane (for 3D-space).

(i) connectivity in multihop n/wk:

→ A semidefinite program is based on connectivity information and considers the position determination as feasible problem. Assuming that position of n anchors are known and m node's position to be determined.

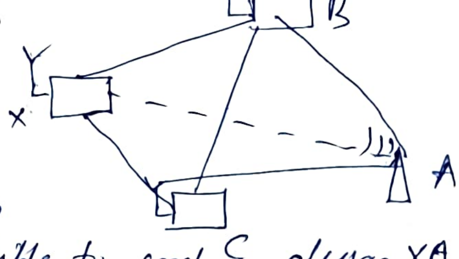
→ The connectivity betn any two node is possible if they are maximum R distance apart. If any two connecting nodes further than R, then it is impossible to choose positions. The observation here is if two nodes are not connected doesnot provide additional informatn.

multidimensional scaling (MDS): on the basis of connectivity betn nodes, an all pair shortest path algorithm roughly estimates position of nodes. The initial estimate is improved by MDS.

Multihop range estimation:

When in multilateration approach node estimates range to atleast 3 anchors to estimate its own position. When anchors doesn't provide the range estimatn to all nodes of n/wk rather only to its neighbors (due to tx. power limitations), then indirect range estimation by multihop commn. able to reuse the well known multilateration algorithm. DV (Distance vector routing)

→ In presence of range estimates and a sufficient no. of neighbors, a node can compute its true Euclidean distance to faraway anchor. Assuming

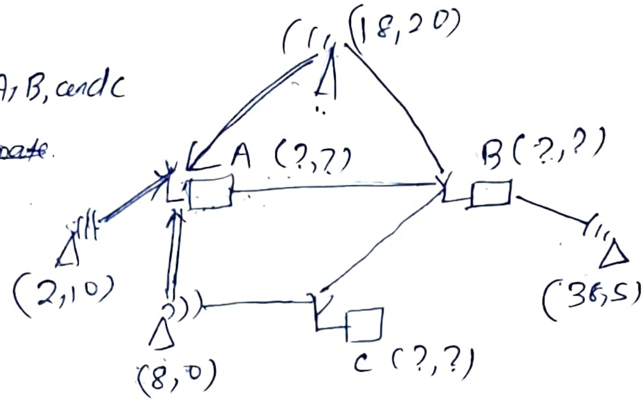


AB, AC, BC, XB, XC are known. It is possible to compute distan XA. (Soln: when X on other side of line BC - node X distinguish these two soln(s) based on local informatn) i) count no. of hops, assume length of on hop known (DV-hop) ii) If range estimates betn neighbors exist, use them to improve total length of route estimatn in previous method (DV-distance)

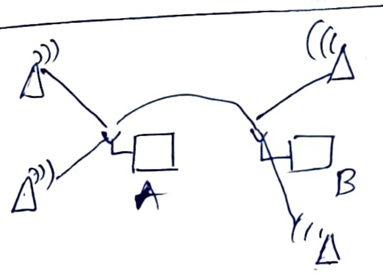
Iterative and collaborative multilateration:

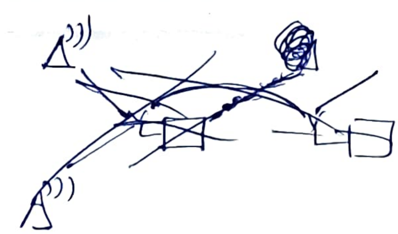
The previous approach tried to estimate distances betn nodes with unknown position and the anchors to apply multilateration with anchors themselves. Alternatively, normal nodes are used after estimation of their positions.

→ For example, as shown in figure nodes A, B, and C are unaware of their position. ~~estimate~~ Node A can triangulate the positn using 3 anchors for its own estimate which in turn provide node C with the missing information for its triangulation. This idea is called iterative multilateration.



→ A particular challenge to this algorithm occurs when not all nodes in the n/work have three nodes with position estimates. So depending on topology it is still possible to estimate some positions through collaborative multilateration.





This scenario is still fully determined as sufficient information available to solve the equation system for two nodes with unknown position (due to collaboration betn A & B)

Probabilistic positioning description & Propagation:

The previous approaches have described the position of a node, once it has been determined by explicit set of coordinates. This limits the uncertainties in range estimates. Some randomness ~~due to~~ is considered by taking probability functn of node's possible location, describing the amount of information available for node's location.

→ Here the prob. density function of a node that relates to distance with which it corresponds to RSSI value from one anchor is obtained.

Once the Prob. density functions ~~&~~ of second distance measurement from second anchor is obtained, the two density functions can be convolved & improved description of ~~B~~ the node's position Probabilities results.