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WIRELESS LOCALIZATION TECHNIQUES

Introduction

A Cyber-Physical-Systems (CPS) is a blend of networks and embedded systems:

- a computer system in which a mechanism is controlled or monitored by some algorithms
- physical and software components are closely connected
- components may move
- interact with each other in ways that change with context

Introduction

A Wireless Sensor Networks (WSN) is a network of spatially dispersed sensors that monitor and record the physical conditions of the environment and forward the collected data to a base station:

- built of "nodes" – from a few to hundreds or thousands, where each node is connected to other sensors
- a node typically has several parts: a radio transceiver, a microcontroller, several sensors and an energy source, usually a battery or an embedded form of energy harvesting
- WSNs can measure environmental conditions such as temperature, sound, pollution levels, humidity, wind etc.

Introduction

- Localization in Cyber-Physical-Systems (CPS) or in Wireless Sensor Networks (WSN) is the **ability to determine the positions of Components, Sensors and Events**
- Localization enables location-aware applications
  - products stored in a warehouse
  - medical personnel or equipment in a hospital
  - firemen in a building on fire
  - monuments/shops nearby
- or supports network services
  - track moving objects
  - report event origin
  - evaluate network coverage
  - assist with routing (Geographical Routing)

Taxonomy

Localization systems consist of two main blocks:

- the set of deployed nodes
- the localization algorithm

Deployed nodes may have different *states:*

unknown

beacon

settled

At the startup of the localization algorithm, nodes can either be in state *beacon* or *unknown*

Nodes

- *Beacon* nodes, also referred to as landmarks or **anchors**, are those that already know their locations through a manual placement or through GPS reading
- *Unknown* nodes, referred to as **target** nodes, are those that do not have any information about their geographic locations
- Over the time, *unknown* nodes may change their states to *settled* if they succeed to determine or estimate their locations
- Both beacon and settled nodes are very useful for unknown nodes in order to estimate their locations, as they could be considered as references

Algorithms

- Localization algorithms aim at finding the location (or position) of unknown nodes
- Ways to determine the location depend on the objective of the cyber-physical application and the underlying technologies
- Global Positioning System (GPS) is the intuitive solution to determine locations accurately. However:
  - not always the most effective solution for CPS, <u>due to cost and energy constraints</u>
  - <u>do not work indoor</u> or when satellites are shielded

GPS-free techniques

- Alternative techniques exploit (i) the sensing and (ii) the wireless communication capabilities of CPS components
- For example:
  - use the Received Signal Strength (RSS), or propagation delay to infer the distances/angles to some reference nodes and then estimate the location through simple geometric computations (e.g. lateration/triangulation techniques)
  - estimate distances by exploiting the difference between heterogeneous waves' propagation properties (e.g., the reception time difference between acoustic and radio waves)
  - **range-free** localization determines unknown node position based on proximity/connectivity information

Topology

Where and *how* the location of a given node is calculated. There are four different system topologies for localization systems:

1. *Remote positioning*: the location of a node is computed at a central base station, where anchor nodes collect transmitted radio signals from the mobile node and forward them to the base station. The latter computes the estimated position of the mobile node based on the measured signals forwarded by the anchors
2. ***Self-positioning***: the location of a node is computed by itself based on the measured signals that it receives from anchor nodes
3. *Indirect remote positioning*: like in the self-positioning case, the node first computes its location and then sends it to a base station through a wireless back channel
4. *Indirect self-positioning*: like in the remote positioning, the location of the mobile node is computed at the base station, then the base station forwards the estimated position to the mobile node, through a wireless back channel

Centralized vs Localized

- *Centralized*: a central device estimates the location of unknown nodes based on the signal measurements forwarded by anchors (e.g., surveillance systems, health care monitoring, environment monitoring, assets tracking)
  - Better accuracy
  - Requires multi-hop network

- *Localized:* each object estimates its location using the collected signal measurements and location information of the anchor nodes in its neighbourhood (e.g., swarm robotics, object auto-navigation, GPS-based systems)
  - Much simpler
  - More iterations/computation -> more energy

Coordinate System

1. *Absolute*: locations are expressed as unique coordinate values with reference to special nodes that know their positions, which are mainly the anchor nodes (4 anchors are needed in a 3D coordinate system)

2. *Relative*: locations are determined relatively to other nodes with no reference to absolute anchors. In other words, in a relative coordinate system reference nodes are not absolute

a. *Physical:* locations are represented as a point in a 2D/3D coordinate system, such as the Universe Traverse Mercator (UTM) system, or the Degree/Minutes/Seconds (DMS) used for GPS

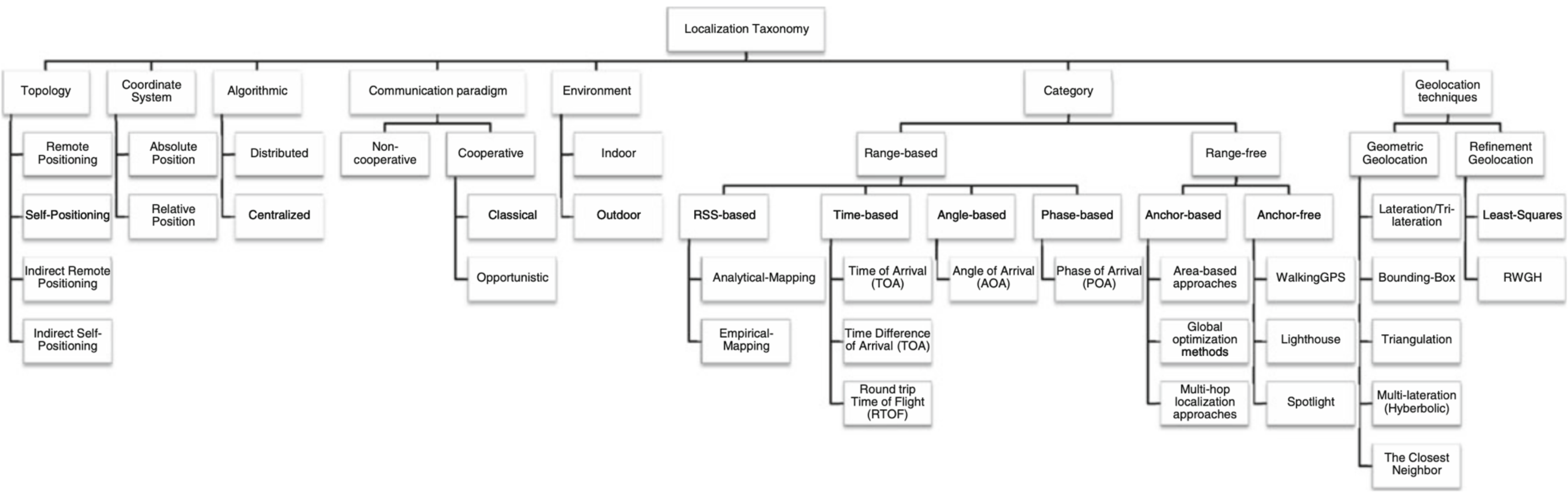
b. *Symbolic:* locations are expressed as logical positions' information such as cell number, office/building number, or street name

Communication Paradigm

How nodes exchange messages between each other:

- *Non-cooperative*:
  - the communication is restricted between unknown nodes and anchors (no communication between nodes with unknown locations)
  - *high density of anchors or long-range anchor transmissions are needed to ensure that each unknown node is within the communication range of at least three anchors*
- *Cooperative:*
  - in addition, it allows communication between unknown nodes
  - *anchor density is alleviated, but more processing is required*
- *Opportunistic*:
  - exploits interactions between existing nodes and other nodes (which may be of heterogeneous nature) that occasionally pass in their proximity
  - *requires efficient node discovery and data exchange*

Taxonomy


Localization Taxonomy
Topology
Coordinate System
Algorithmic
Communication paradigm
Environment
Category
Geolocation techniques
Remote Positioning
Self-Positioning
Indirect Remote Positioning
Indirect Self-Positioning
Absolute Position
Relative Position
Distributed
Centralized
Non-cooperative
Cooperative
Classical
Opportunistic
Indoor
Outdoor
Range-based
Range-free
RSS-based
Time-based
Angle-based
Phase-based
Analytical-Mapping
Empirical-Mapping
Time of Arrival (TOA)
Time Difference of Arrival (TOA)
Round trip Time of Flight (RTOF)
Angle of Arrival (AOA)
Phase of Arrival (POA)
Anchor-based
Anchor-free
Area-based approaches
Global optimization methods
Multi-hop localization approaches
WalkingGPS
Lighthouse
Spotlight
Geometric Geolocation
Refinement Geolocation
Lateration/Tri-lateration
Bounding-Box
Triangulation
Multi-lateration (Hyperbolic)
The Closest Neighbor
Least-Squares
RWGH

Performance metrics

Accuracy: mean distance error, usually the average Euclidean distance between the estimated and the true location.

Precision: reveals the variation in algorithm's performance over many trials. Usually, the cumulative probability functions (CDF) of the distance error.

Complexity: can be attributed to hardware, software, and operation factors. Usually, location rate is an indirect indicator for complexity.

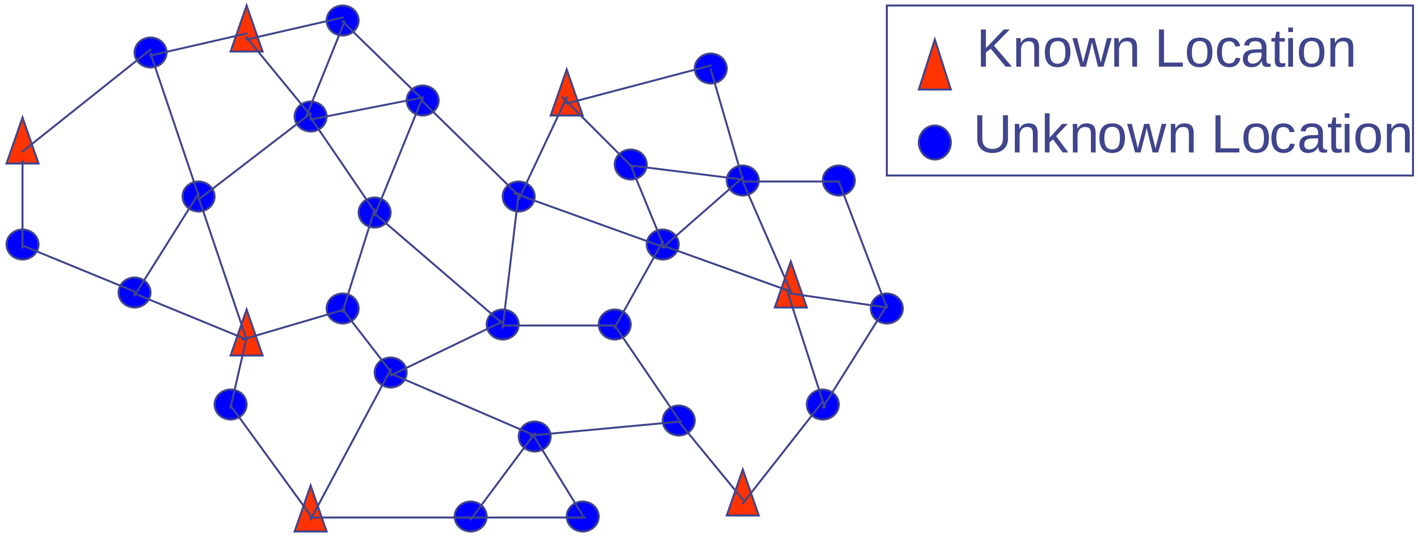
Robustness: the system's capability of working when some signals are not available (e.g., when some of the RSS value or angle character are never seen before).

Scalability: the positioning performance degrades when the distance between the transmitter and receiver increases. A location system may need to scale on two axes: geography and density.

Cost infrastructure, maintenance, additional nodes...

Anchor-based methods

Most proposals utilize *beacon* nodes to work as reference nodes



Range-Based Methods

- Location discovery consists of two phases:
  - Ranging phase
  - Estimation phase
- Ranging phase (measuring distance):
  - Each node computes its distance or angle from neighbors (anchors)
- Estimation phase (combining distance):
  - Nodes use <u>range information</u> and <u>anchors' locations</u> to estimate their positions

Ranging phase

Distance measuring methods:

- Strength of wireless signal
  - Uses Received Signal Strength Index (RSSI) readings
- Time of Arrival (ToA, TDoA)
  - Used with radio, acoustic, ultrasound
- Angle of Arrival (AoA)
  - Measured with directive antennae or arrays of antennae

Received Signal Strength (RSS)

- Target nodes estimate the distance from anchors using the attenuation of emitted signal strength
- In free space, the RSS varies as the inverse square of the distance *d* between the transmitter and the receiver:

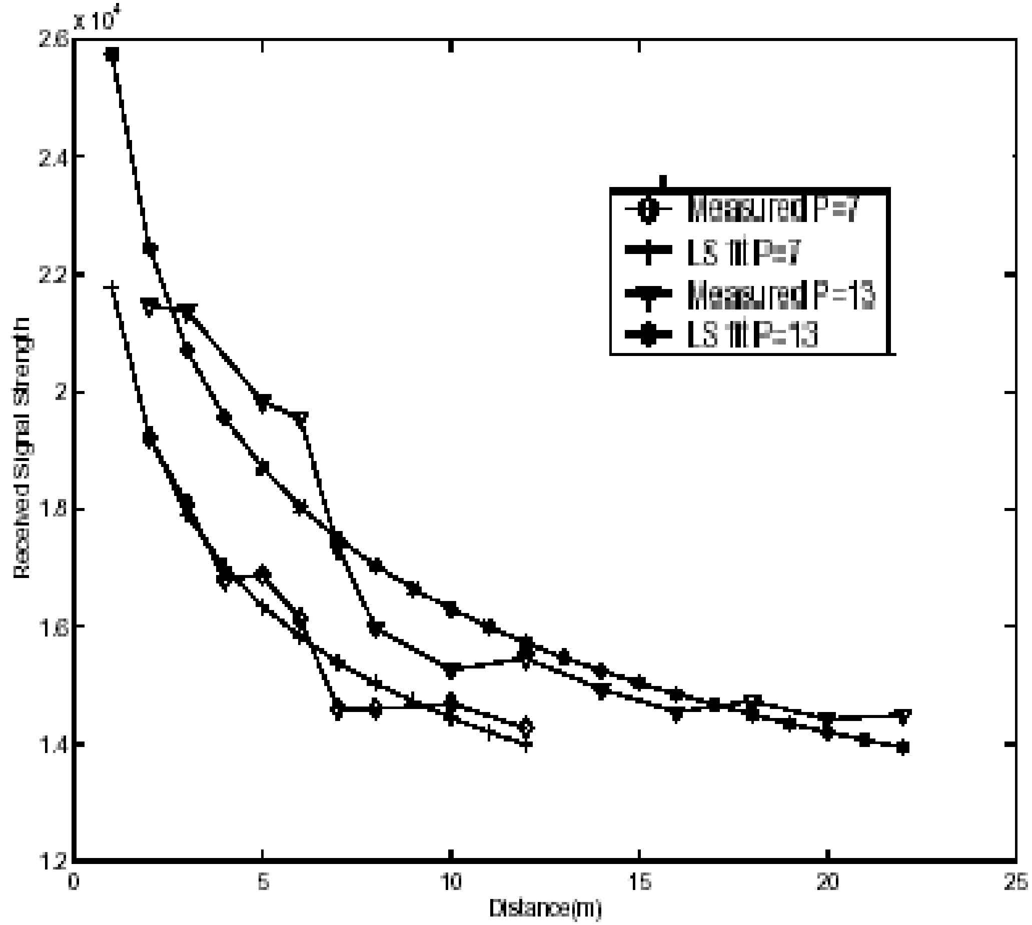
$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

- Due to multipath fading and shadowing (reflection, refraction, diffraction, scattering) present in the indoor environment, background interference, irregular signal propagation, path-loss models do not always hold
- The signal is weaker and more exposed to errors
- The parameters employed in these models are *site-specific*

Site-specific RSS

- Radio Frequency signal attenuation is a (reverse-proportional) function of distance
- An empirical model is derived by obtaining a least square fit for each power level

$$P_{RSSI} = \frac{X}{r^n}$$

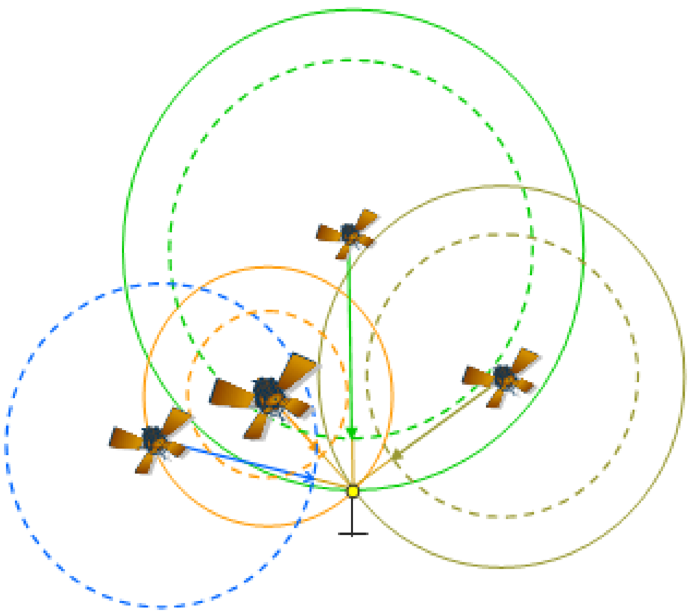


Comparison between RSS-based techniques

Technique	Advantages	Limitations
Analytical-mapping models	Simple to implement Useful for simulators design	Parameters are environment-dependent Coarse accuracy
Empirical-mapping models	Can achieve high accuracy level	Need extensive environment profiling High off-line computation overhead Poor scalability Unreliable if the environment is continually changing

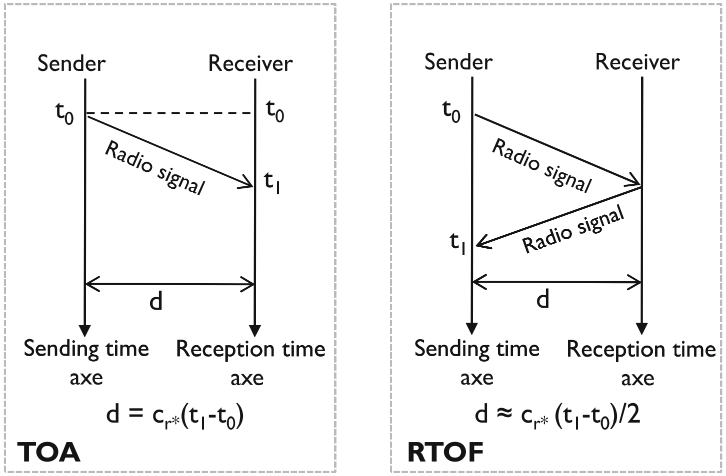
Time of Arrival (ToA)

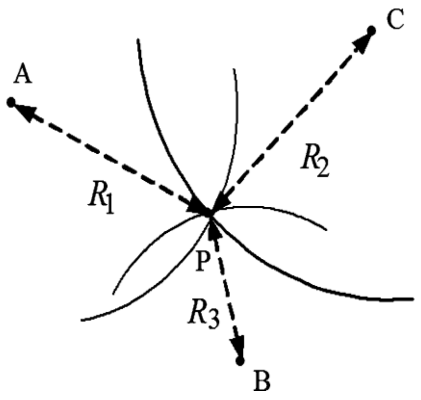
- Example: GPS
- Uses a satellite constellation of at least 24 satellites with atomic clocks
- Satellites broadcast time and their positions
- Estimate distance to satellite using signal ToA
- Use Trilateration



Time of Arrival (ToA)

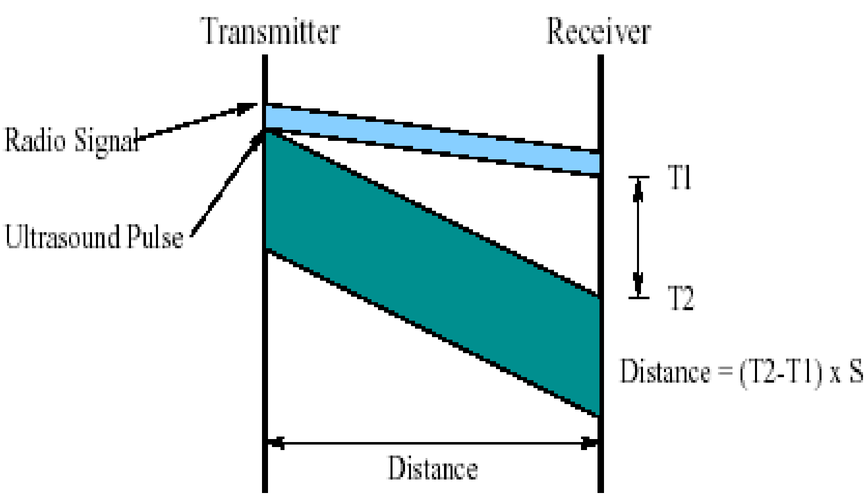
- The distance from the anchor is proportional to the RF signal propagation time. In 2D positioning, ToA measurements must be made with respect to <u>at least three</u> anchors (A, B and C)
- The one-way propagation time is measured and multiplied by the speed of the RF signal
- Problem: at speed of light: 1ms → 300km
  - <u>transmitters and receivers must be synchronized precisely</u>

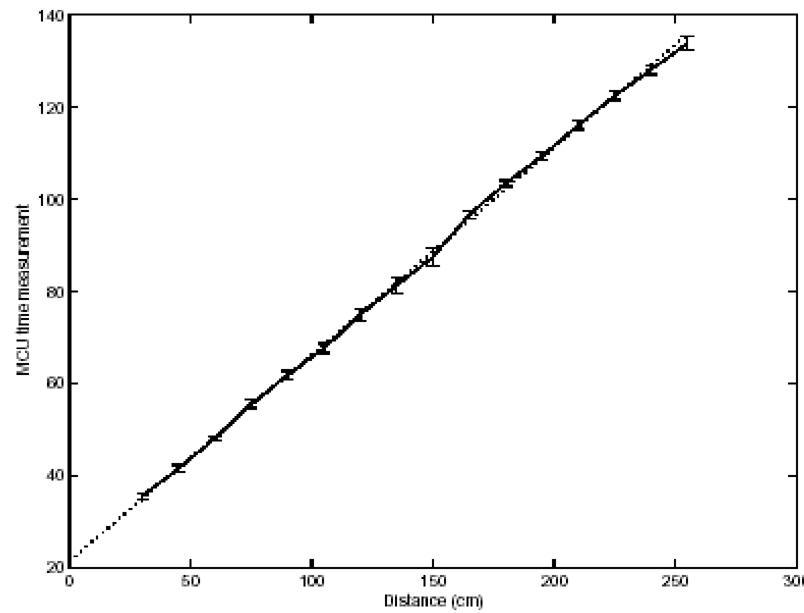




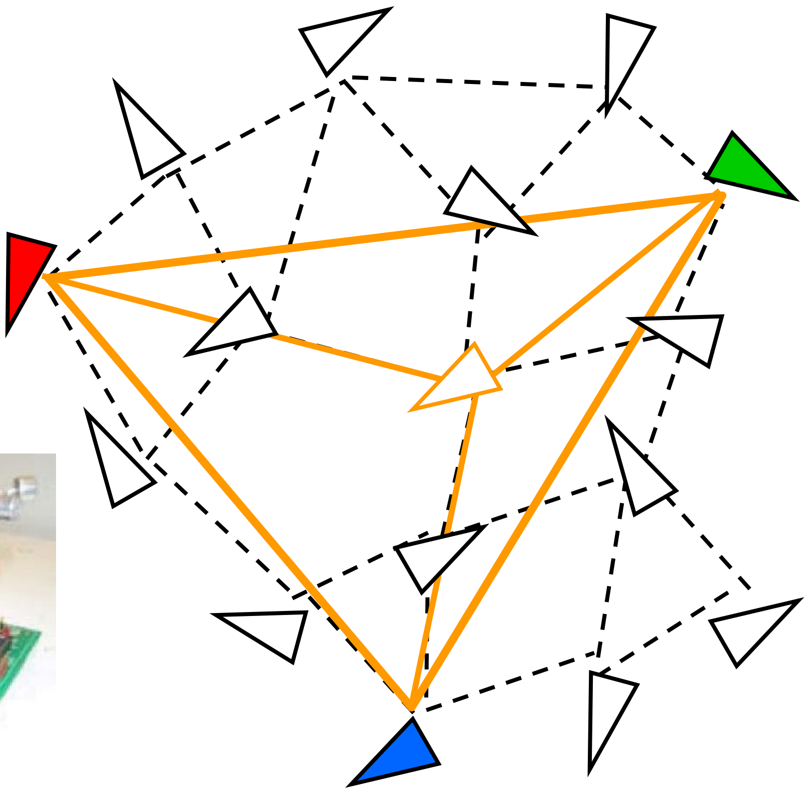
Time Difference of Arrival (TDoA)

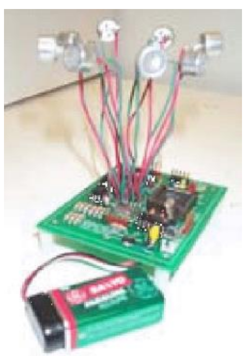
- ToA using RF and Ultrasound
  - calculate the time difference between RF and ultrasound (T2-T1)
  - <u>estimate distance using the speed of sound (S)</u>
- Energy-consuming
- Extra hardware





Angle of Arrival (AoA)





- Use directional antenna or array of antennae
- 3 measuring units for 3D and 2 measuring units for 2D positioning
- No time synchronization needed
- Estimate relative angles between neighbors
- Location derived from the intersection of several pairs of angle direction lines

Angle of Arrival (AoA)

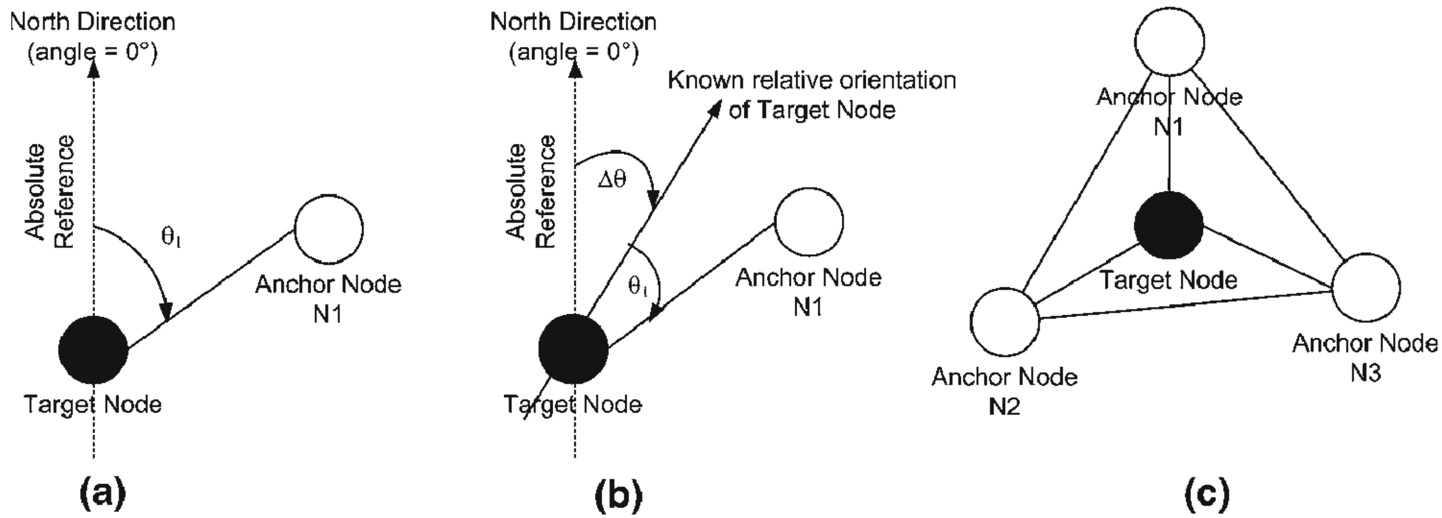


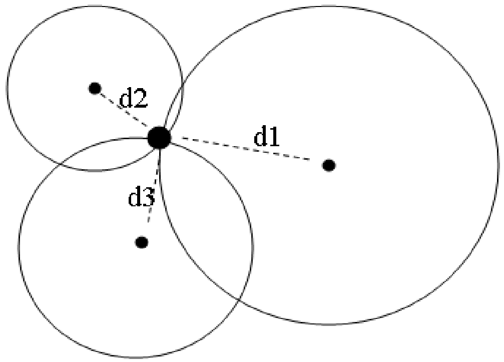
Fig. 7 AOA orientation concept. **a** Absolute orientation. **b** Relative orientation. **c** AOA with unknown orientation

- Require additional hardware and is expensive to deploy in large sensor networks

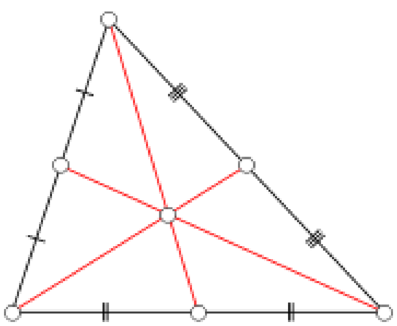
Anchor-based estimation methods

... after evaluating the distance between targets and anchors by:

- Trilateration (Range-based)

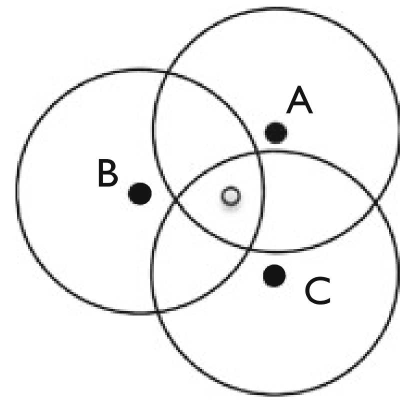


- Centroid (Range-free)

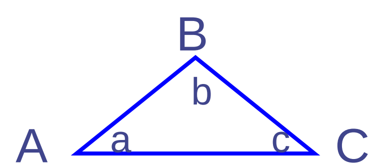


Estimation phase

- Trilateration (with noisy measurements)
  - Determine the location by knowing distance from anchors



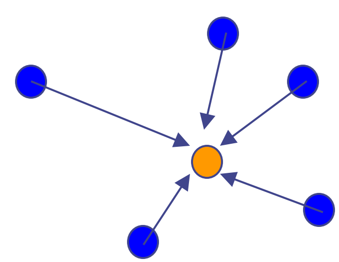
- Triangulation
  - Determine the location by knowing angles between reference points



Sines Rule $\frac{A}{\sin a} = \frac{B}{\sin b} = \frac{C}{\sin c}$

Cosines Rule
$$C^2 = A^2 + B^2 - 2AB\cos(c)$$
$$B^2 = A^2 + C^2 - 2BC\cos(b)$$
$$C^2 = B^2 + C^2 - 2BC\cos(a)$$

- Multi-lateration
  - Considers all available beacons



Range-Based limitations

- Many range-based localization schemes are based on assumptions that <u>do not always hold or are impractical</u>
- Among them:
  - circular radio range
  - symmetric radio connectivity
  - additional hardware (e.g., ultrasonic)
  - lack of obstructions
  - clear line-of-sight
  - no multipath and flat terrain

Range-Free Localization

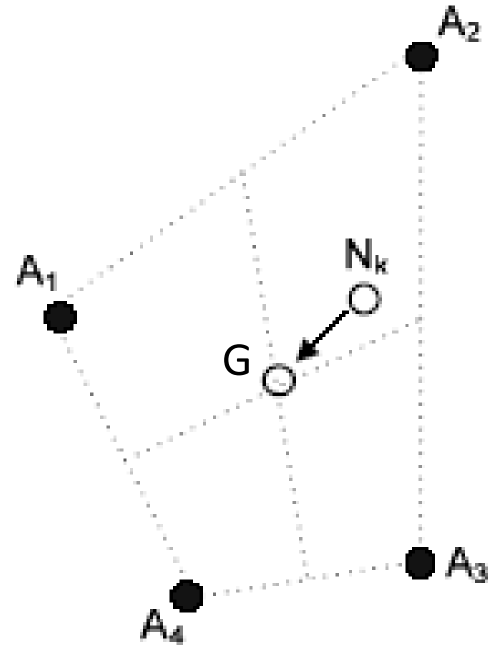
- Nodes never tries to estimate their absolute distance from anchors
  - Range-free methods do not rely on distance or angle estimation. They rather use proximity or connectivity information to devise the location of the target

- Area-based approaches:
  - **Centroid Localization**
  - **APIT (Approximate Point-In-Triangle test)**
- Multihop localization approaches
  - **DV-HOP**

- Advantages
  - Cheap hardware
  - Low computational power
- Disadvantages
  - Less accuracy than Range-Based methods

Range-Free Localization: Centroid Method

- *Area-based approach*: based on radio connectivity between the target and anchors, estimate the position of the target as a particular point inside a polygon
- After beacon listening, the target N_k computes its position as the *centroid* point G, defined as the geometric center of gravity (or barycenter) of the polygon formed by the set of anchors



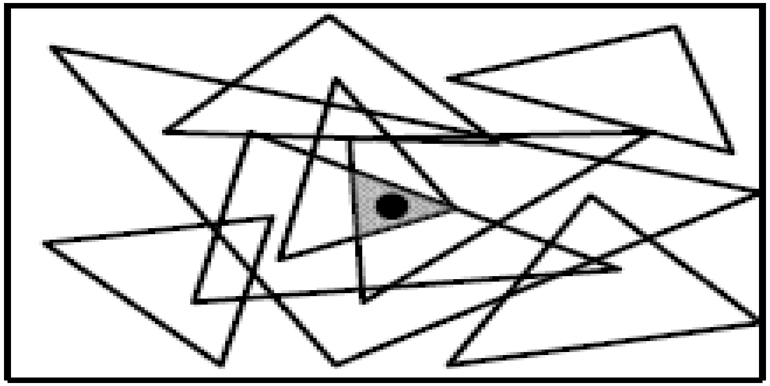
$$(X_G, Y_G) = \left(\frac{\sum_{i=1}^{n}(X_i)}{n}, \frac{\sum_{i=1}^{n}(Y_i)}{n} \right)$$

Range-Free Localization: Centroid Method

- Advantages
  - Simple and easy to implement
  - Small overhead (use of few beacons, simple computation)
- Drawbacks
  - Small accuracy
  - Needs overlapped anchors’ radio ranges for correct estimation (or high density of anchors)

Range-Free Localization: APIT

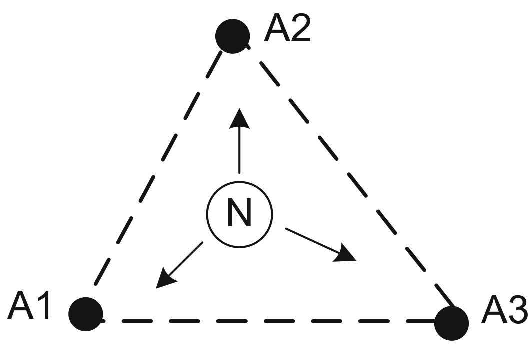
- *Approximate Point-In-Triangulation* (APIT) employs a novel area-based approach to perform a centroid-based location estimation by isolating the environment into triangular regions
- It assumes that the location of the target is the center of gravity of a certain triangle, which is defined as the intersection of triangles formed by anchors in which the target node resides

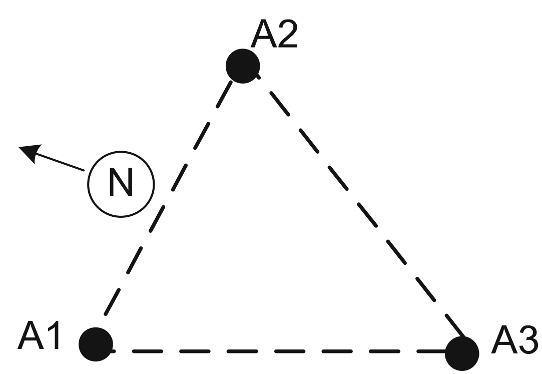


Proposed by He, Huang, Blum, Stankovic and Abdelzaher in [2003]

Range-Free Localization: APIT

- The idea consists in dividing the environment into triangular regions, then testing **whether the target is inside a given triangle or not** to narrow down the area of the possible target locations
- It is based on the *Point-In-Triangulation Test* (PIT)
- The PIT determines whether a node N with unknown position is <u>inside</u> the triangle formed by anchors A1, A2 and A3, or <u>outside</u>





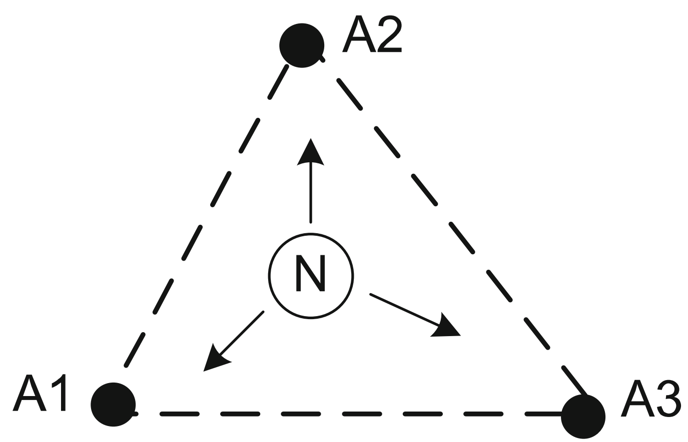
Range-Free Localization Methods: APIT

Each node works as follows:

Receive location beacons (X_i, Y_i) from N anchors;
$InsideSet = \emptyset$;
for each triangle $T_i \in \binom{N}{3}$ triangles **do**
  if Point-In-Triangle-Test (T_i) == TRUE **then**
    $InsideSet = InsideSet \bigcup T_i$;
  end if
end for
Estimated Position = CenterOfGravity($\bigcap T_i \in InsideSet$);

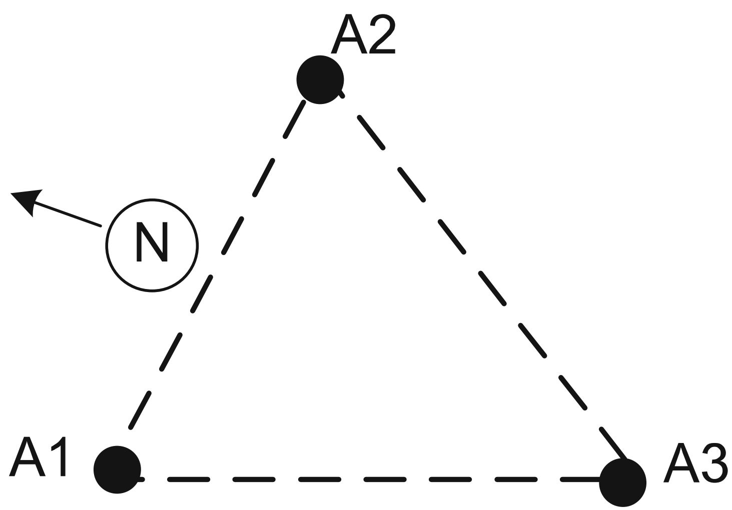
Perfect PIT test

Proposition 1: If N is <u>inside</u> the triangle, when N moves in any direction, it will get close to (or further from) <u>at least one</u> anchor.



Perfect PIT test

Proposition 2: If N is <u>outside</u> the triangle, there exists a direction so that, when N moves along it, it goes farther (or closer) to <u>all the three</u> anchors at the same time.



Performing the PIT test

- The perfect PIT test is unfeasible in practice:
  1. nodes typically do not move, and do not have the ability to recognize the direction without moving
  2. not possible to perform an exhaustive test covering all possible directions in which the target may move to

- *Solution*: an approximation has been proposed. The idea is to use neighborhood information, exchanged via beaconing, to emulate the node movement in the Perfect PIT

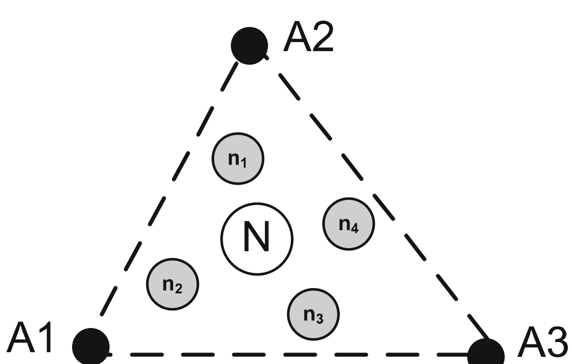
Approximate PIT (APIT) test

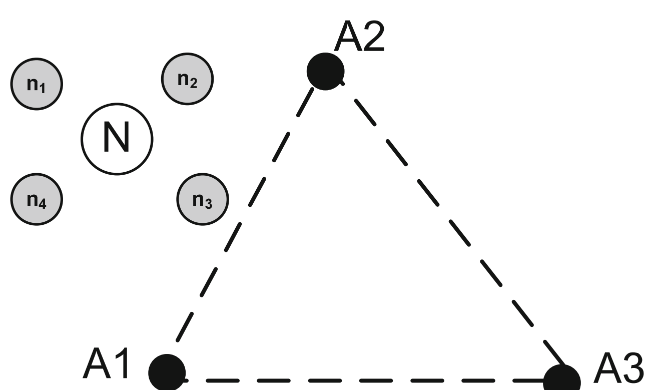
1. The target node asks its neighbors for their *distances* to three corner anchors
2. The target then compares its *distance* to these three corner anchors against those of its neighbors
3. If no neighbor is farther from (or closer to) all three anchors simultaneously, then the target assumes itself as being **inside triangle**. Otherwise, the target assumes it is outside the triangle

Approximate PIT Test

N denotes the target node, *Ai* denotes the *i* th anchor:

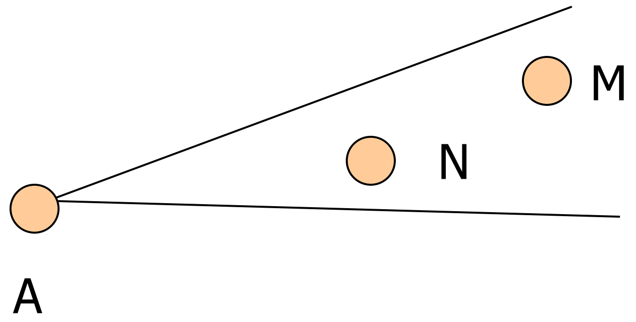
- The *left figure* shows that if the *N* is inside the triangle, none of its neighbors is either closer to or farther from all anchors
- In the *right figure*, if *N* is outside the triangle, its neighbor *n*1 (*n*3) indicates that there exists a direction along which to be farther (closer) to all anchors





Relative Distance Estimation

- Experiments show that, in the absence of obstacles, the received signal strength (RSS) decreases as the receiver moves away from the transmitter
- *Relative distance estimation*: the further away a node is from the anchor, the weaker the received signal strength

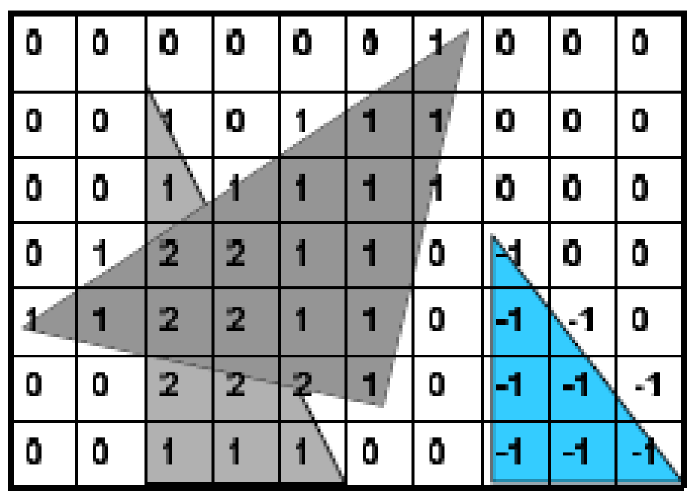


RSS(A,M) < RSS(A,N)

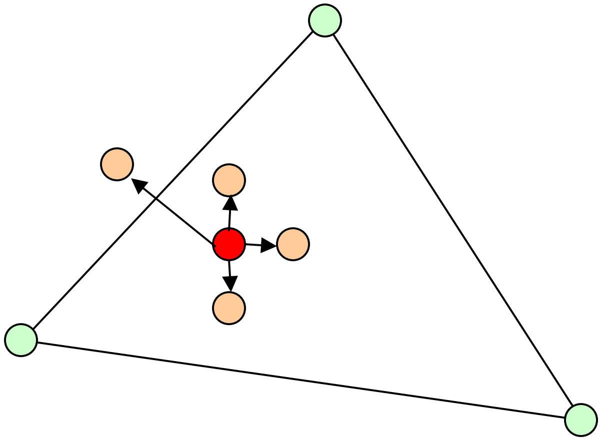
DIST(A,M) > DIST(A,N)

APIT aggregation

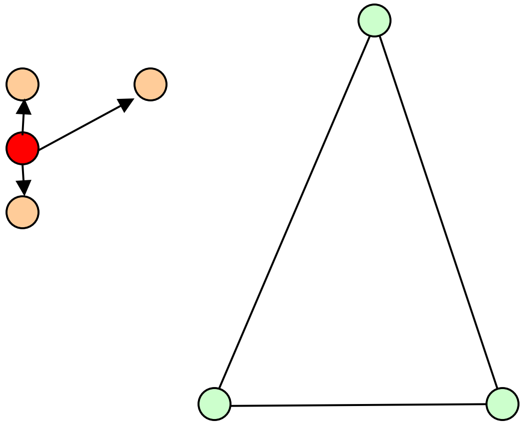
- Represent the maximum area in which a node will likely reside using a grid SCAN algorithm
  - For **inside** decision the grid regions are incremented
  - For **outside** decision the grid regions are decremented



Error Scenarios for APIT test



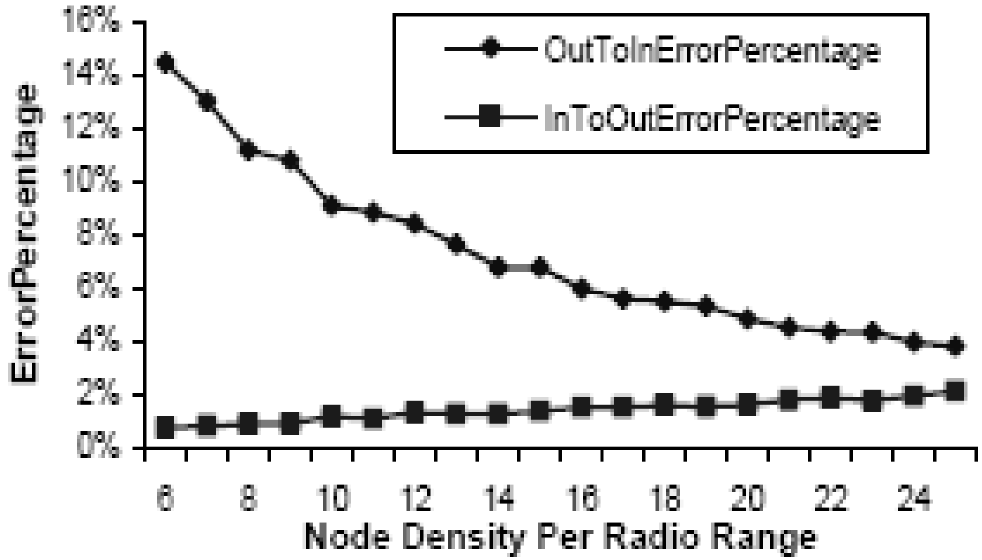
In-to-out error



Out-to-in error

Range-Free Localization Methods: APIT

- Experimental results show that the error percentage is small as the node density increases



Range-Free Localization Methods: APIT

- Advantages
  - Small overhead
  - More accurate results than centroid method
- Drawbacks
  - Problem determining a node located out of all anchor triangles (undetermined target)

Range-Free Localization Methods: Multihop localization approaches

- Because of the limitation of the transmission power, it is not always possible that a target trying to locate itself is in communication range with at least three anchor nodes
- Mechanisms for multihop localization have been proposed to extend the localization process over a larger geographical extent

Range-Free Localization: Distance propagation Methods

- *DV-HOP* consists in flooding the network such that each anchor independently broadcasts a *beacon*, embedding its location and a hop-counter field initially set to one and increased in each new hop
- Then, each target node identifies the shortest-path to each anchor node and tries to estimate its distance to it
- The idea is to compute the number of hops between any two anchors (*Ai*, *A j*) and estimate the average 1-hop distance by dividing the sum of physical distances by the sum logical distances

Proposed by Niculescu and Nath in [2001] as Ad-Hoc Positioning System

Range-Free Localization: DV-HOP

- *Node update phase*: When a target N_i receives a beacon from an anchor A_i, it maintains the record (X_i, Y_i, h_i) for each anchor, where (X_i, Y_i) represents the location of the anchor, and h_i the number of hops from N_i to that anchor A_i.
- Then, N_i <u>increments h_i and forwards</u> the beacon to neighbours in its radio range
- At the end of this step, targets know about the locations of anchor nodes and the hop counts to reach them

Range-Free Localization: DV-HOP

- *1-hop distance estimation phase*: When an anchor receives the locations and hop counts to other anchors, it calculates the estimated average 1-hop distance, referred to as *correction factor ci*, expressed as follows:

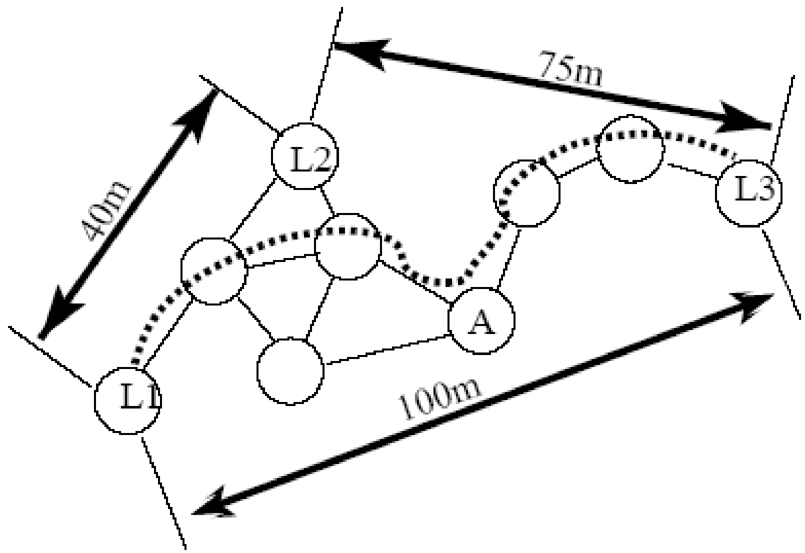
$$c_i = \frac{\sum\left(\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\right)}{\sum(h_i)}$$

where *i* is the anchor that calculates correction, *j* are anchors known to *i, x and y* are anchor coordinates, *h* is the hop count from anchors

Range-Free Localization: DV-HOP

- Then, the anchor floods the network with the estimated correction factor. A node that receives a correction, forwards it and then stops forwarding subsequent corrections
- *Target node localization*: each target uses the correction received from the closest anchor as the estimated 1-hop distance. It then multiplies the 1-hop distance by the hop counts to other anchors to estimate its physical distances to them
- After getting distance estimates to at least three anchors, a target can use trilateration to approximate its location

Range-Free Localization: DV-HOP



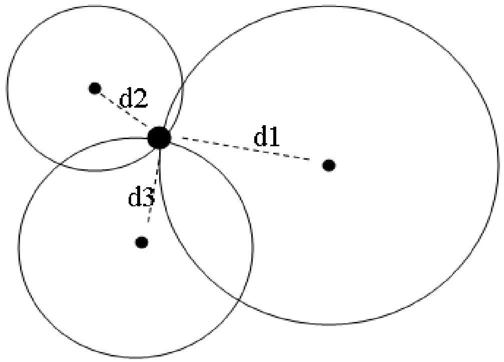
L_1 computes the correction $\frac{100+40}{6+2} = 17.5$.
L_2 computes a correction of $\frac{40+75}{2+5} = 16.42$
L_3 a correction of $\frac{75+100}{6+5} = 15.90$.
A gets its correction from L_2

Distance to L1 = 3 x 16.42, to L2 = 2 x 16.42, to L3 = 3 x 16.42

Range-Free Localization: DV-HOP

... after evaluating the distance between targets and anchors:

- Trilateration (Range-based)



Range-Free Localization: DV-HOP

- Advantages
  - straight with multi-hop networks
- Drawbacks
  - Estimation error depends on the number of anchors that a node can hear
  - Works only for isotropic networks (uniformity in all orientations). In fact, for anisotropic environment, the average 1-hop distance will not be accurate as connectivity will be less correlated with range
  - Inter-target communication overhead

Conclusion

- Localization is important in CPS and WSN
- Many proposals presented to address localization issues
- Range-Based localization techniques are accurate but costly
- Range-Free localization techniques are cheap but inaccurate