Wireless Sensor Network Localization Techniques

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Introduction

- Self-localization capability highly desirable in environmental monitoring applications such as :
  - Bush fire
  - Surveillance
  - Water quality monitoring
  - Precision agriculture
  - Inventory management
  - Intrusion detection
  - Road traffic monitoring
  - Health monitoring
  - Reconnaissance

Why We Need Localization?

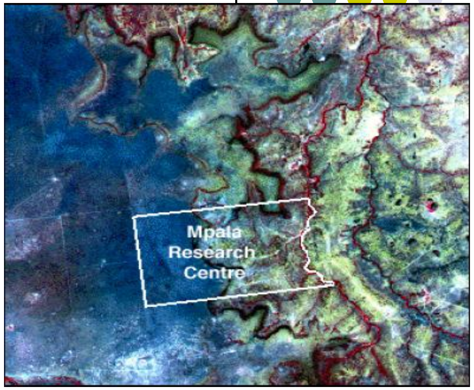
- Two types of applications
  - Some need global coordinate system
  - Some need local coordinate system
- Some constraints cause most sensors do not know their locations:
  - Cost and size of sensors
  - Energy consumption
  - Implementation environment
  - Deployment of sensors
- Sensors with unknown location information are called non-anchor nodes.
  - Their coordinates will be estimated by the sensor network localization algorithm.

What is Localization?

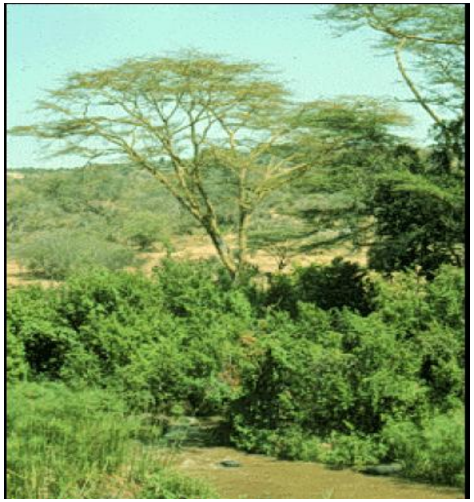
- Estimation the locations of sensors with initially unknown location information.
- It uses knowledge of the absolute positions of a few sensors and inter-sensor measurements such as:
  - distance and bearing measurements.
- Sensors with known location information are called anchors
- Anchors locations can be obtained by using:
  - Global Positioning System (GPS)
  - Installing anchors at points with known coordinates

Example: ZebraNet Sensor Network

- Biologists want to track animals to study:
  - Interactions between individuals.
  - Interactions between species.
  - Impact of human development.



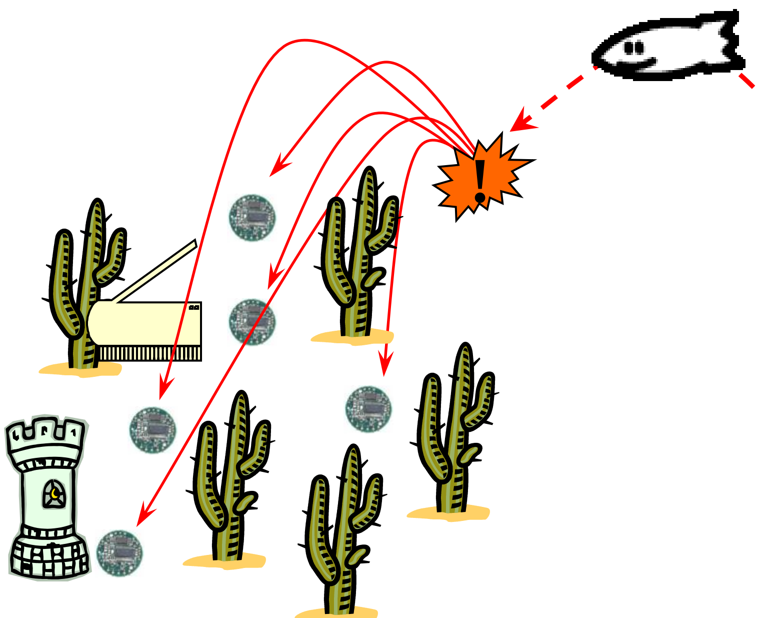
- Current tracking technology: VHF collar transmitters
- ZebraNet:
  - Mobile sensor net with intermittent base station.
  - Records position using GPS every 3 minutes.
  - Records Sun/shade info.
  - Detailed movement information (speed, movement signature) 3 minutes each hour.
  - Future: head up/head down, body temperature, heart rate, camera.
- Goal, full ecosystem monitoring (zebras, hyenas, lions…).

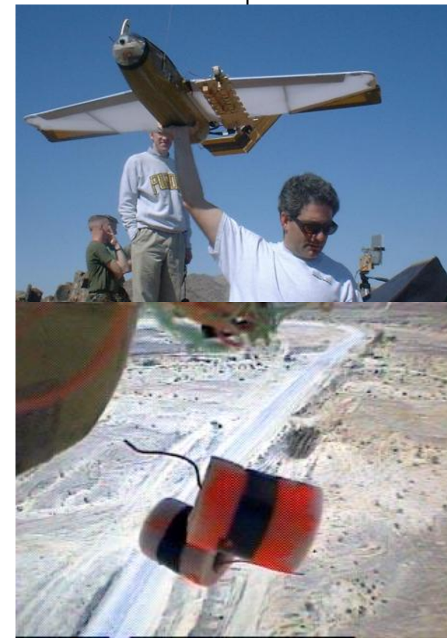


Military Applications

- Intelligence gathering (troop movements, events of interest).
- Detection and localization of chemical, biological, radiological, nuclear, and explosive materials.
- Sniper localization.
- Signal jamming over a specific area.

- Visions for sensor network deployment:
  - Dropped in large numbers from UAV.
  - Mortar-Launched.





Is Positioning Necessary?

- YES!
- Can be the mean or the goal of a WSN application
- Is used as building block in:
  - Routing protocols
  - Data dissemination protocols
  - Localization as application of WSN

Example: Geographic Routing

- Allows development of algorithms with better scalability
- Position centric addressing first proposed in 1970's
  - Recent growing interest for it
- Nodes are addressed by their location instead of ID
- No additional job required to support routing
- State of the packet (position) and destination position are sufficient
- Simplest algorithm: Cartesian routing
- Stojmenovic (IEEE Commun.Magazine 2002) presents several strategies for geographical routing

Problem Statement

- Regular assumptions for WSN protocol test scenarios:
  - Large number of nodes
  - Random deployment in a (known shape) given area
  - Known (identical) transmission range for all nodes
  - Static/not very dynamic networks
- Question:
  - What are the geographical positions of the nodes?
    - Absolute positioning
    - Relative positioning

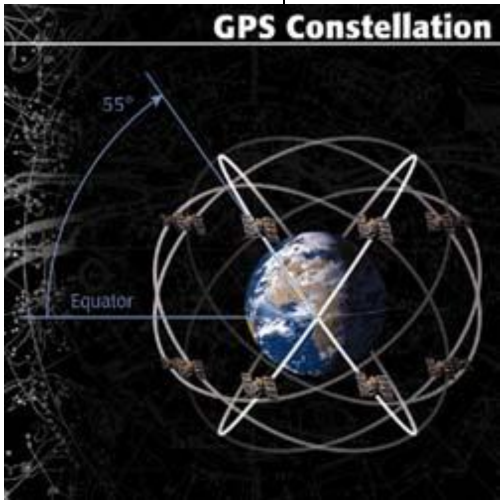
A Possible Solution?

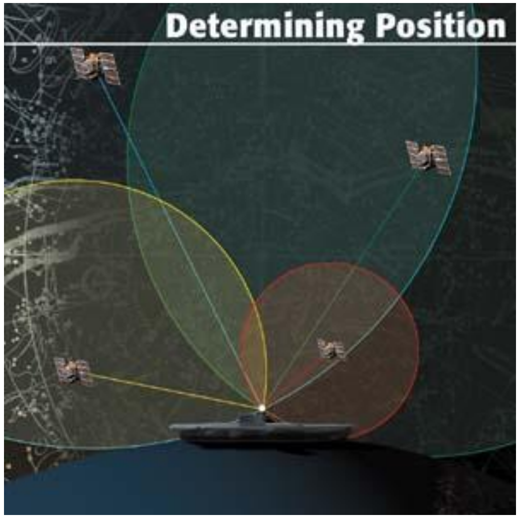
- Usage of Global Positioning System (GPS) devices
- Not a feasible solution for WSN:
  - High cost of the device (value/energy/computation power/space)
  - Unavailability/poor precision of the service in special environments (indoors, underground, etc.)
- Conclusion:
  - Other approaches need to be developed and deployed

Why is Localization a Non-Trivial Problem?

- Manual configuration
  - Unscalable and sometimes impossible.

- Why not use GPS to localize?
  - Hardware requirements vs. small sensors.
  - Obstructions to GPS satellites common.
    - GPS satellites not necessarily overhead.
    - Doesn't work indoors or underground.
  - GPS jammed by sophisticated adversaries.
  - GPS accuracy (10-20 feet) poor for short range sensors.
- Conclusion: other approaches need to be developed and deployed





Classification

- Different aspects of localization studied in:
  - Vision,
  - Robotics
  - Signal processing
  - Networking,
  - …
- Solutions can be classified in several manners:
  - One-hop or multi-hop schemes
  - Range free or range based schemes
  - Absolute, relative or local coordinates
  - Centralized, distributed or localized algorithms

Measurement Techniques

- Most Localization algorithm use measurement techniques.
- 3 Different approaches:
  - Angle-of-Arrival measurements (AOA)
    - Use of the receiver antenna's amplitude response
    - use of the receiver antenna's phase response.
  - Distance related measurements
  - Received Signal Strength (RSS) profiling measurements

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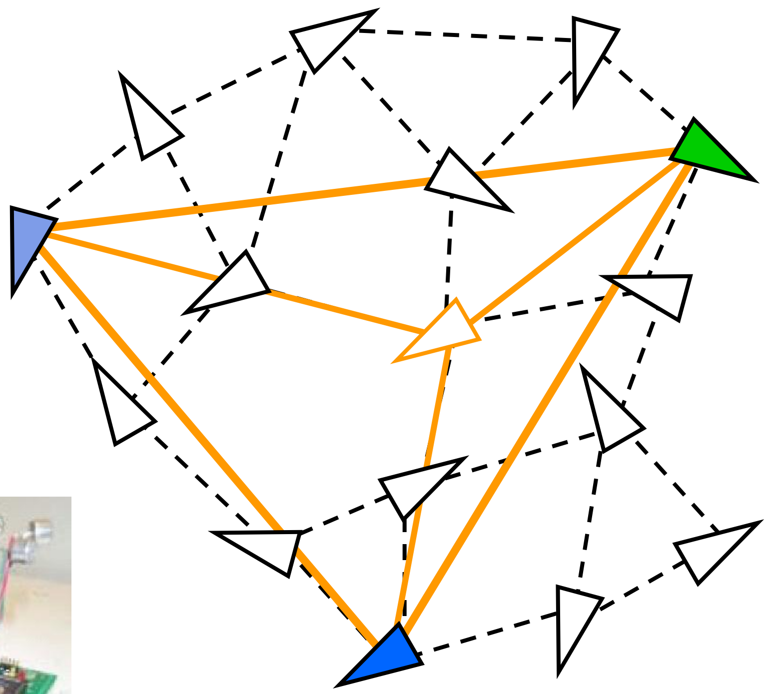
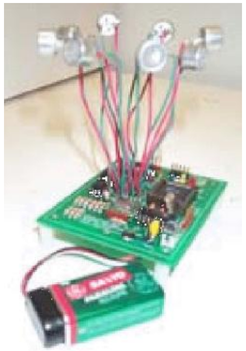
Angle of Arrival (AOA)





"Medusa" mote

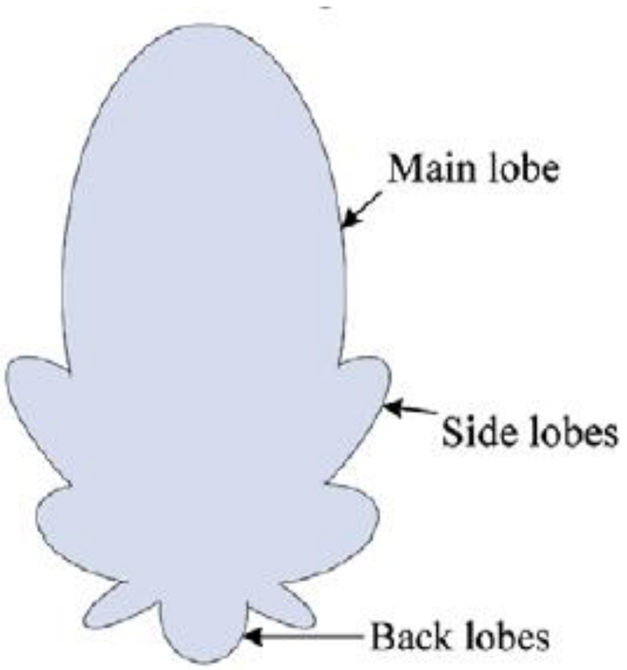
- Idea: Use antenna array to measure direction of neighbors
- Special landmarks have compass + GPS, broadcast location and bearing
- Flood beacons, update bearing along the way
- Once bearing of three landmarks is known, calculate position

AOA Measurements: Receiver Antenna's Amplitude Response

- Beamforming is the basis of one category of AOA measurement.
- It uses anisotropy in the reception pattern of an antenna
- The measurement unit can be of small size in comparison with the wavelength of the signals

Receiver Antenna's Amplitude Response

- Characteristics:
  - The beam of the receiver antenna is rotated electronically or mechanically
  - The direction corresponding to the maximum signal strength is taken as the direction of the transmitter.
- Problem :
  - In some cases the transmitted signal has a varying signal strength



Dealing With Varying Signal Strength Problem

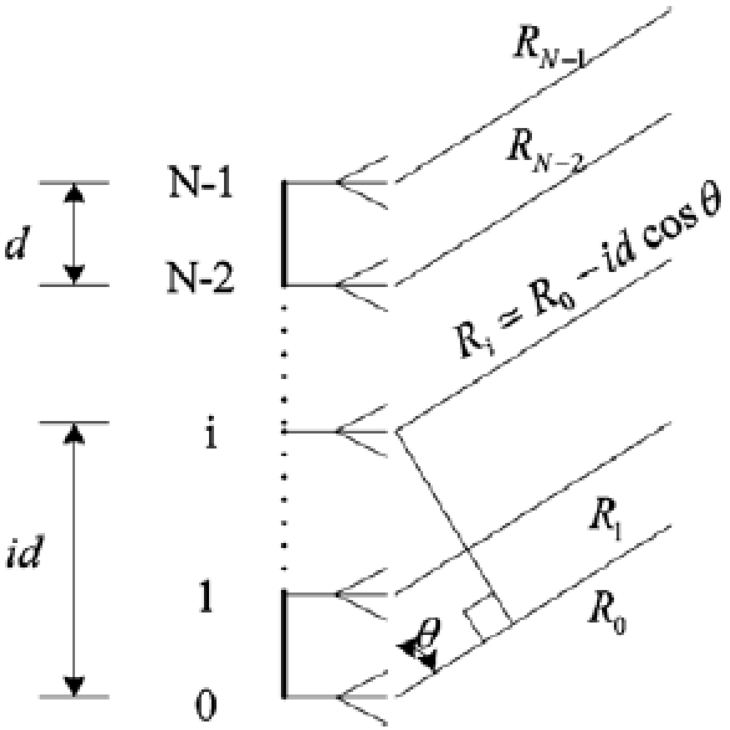
- Method 1:
  - Using a second non-rotating and omni directional antenna at the receiver.
  - By normalizing the signal strength received by two antennas
- Method 2:
  - Using a minimum of two (but typically at least four) stationary antennas with known, anisotropic antenna patterns
  - Overlapping of these patterns and comparing the signal strength received from each antenna at the same time yields the transmitter direction

AOA Measurements: Receiver Antenna's Phase Response

- Interferometry
  - Measurements of the phase differences in the arrival of a wave front
- It typically requires a large receiver antenna (relative to the wavelength of the transmitter signal) or an antenna array
- It works quite well for high SNR
- It may fail in the presence of strong co-channel interference and/or multipath signals

Receiver Antenna's Phase Response

- $R_i = R_0 - id\cos\theta$
  - *Ri* is the distance between the transmitter and the ith antenna element
  - *d* is distance between antennas
  - θ is the bearing of the transmitter with respect to the antenna array

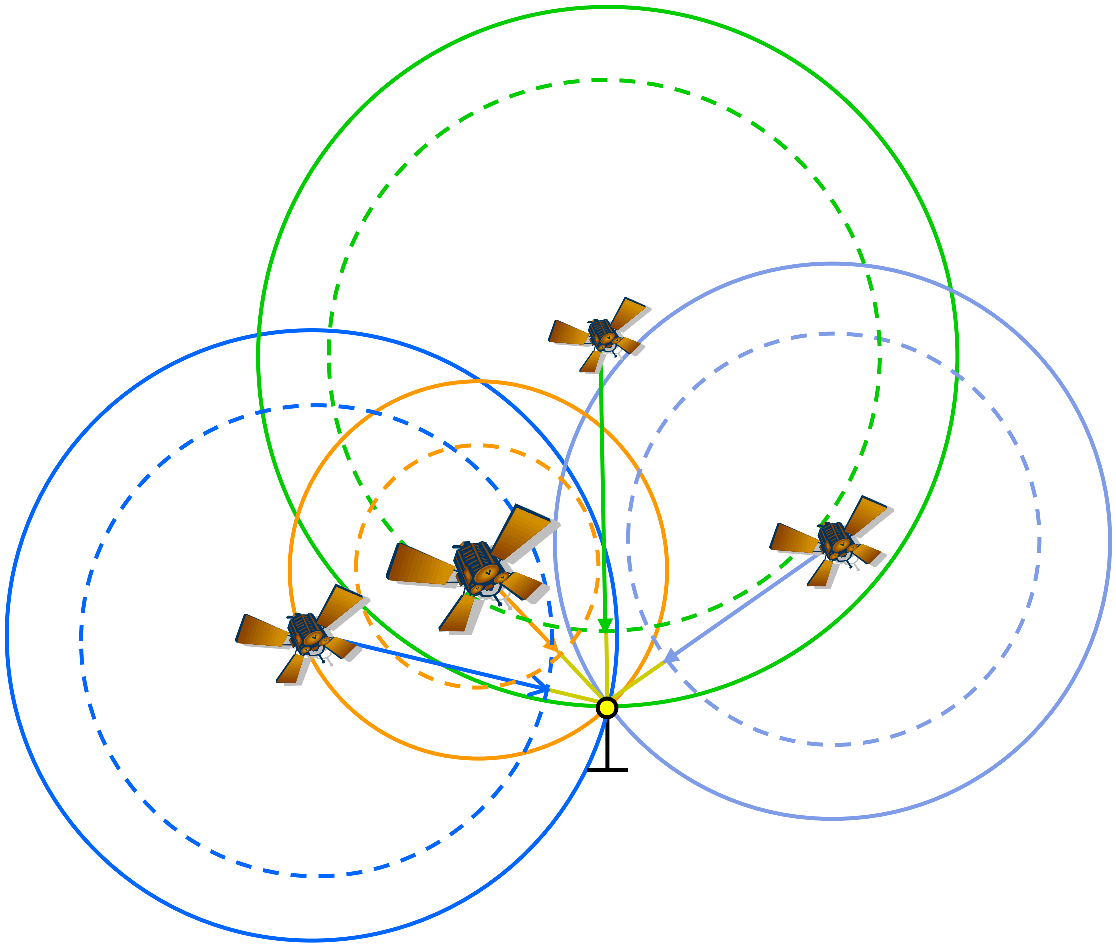


The transmitter signals received by adjacent antenna elements have a phase difference of $2\pi\frac{d\cos\theta}{\lambda}$, which allows us to obtain the bearing of the transmitter from the measurement of the phase difference.

Measurement Techniques

- Angle-of-arrival measurements (AOA)
  - Use of the receiver antenna's amplitude response
  - use of the receiver antenna's phase response.
- Distance related measurements
- Received signal strength (RSS) profiling measurements

Time of Arrival (TOA)



- Example: GPS
- Uses a satellite constellation of at least 24 satellites with atomic clocks
- Satellites broadcast precise time
- Estimate distance to satellite using signal TOA
- Trilateration

Distance Related Measurements

- Distance related measurements include:
  - Propagation time based measurements
    - One-way propagation time measurements
    - Roundtrip propagation time measurements
    - Time-Difference-of-arrival (TDOA) measurements
  - Distance estimation via received signal strength measurements

One-way Propagation Time Measurements

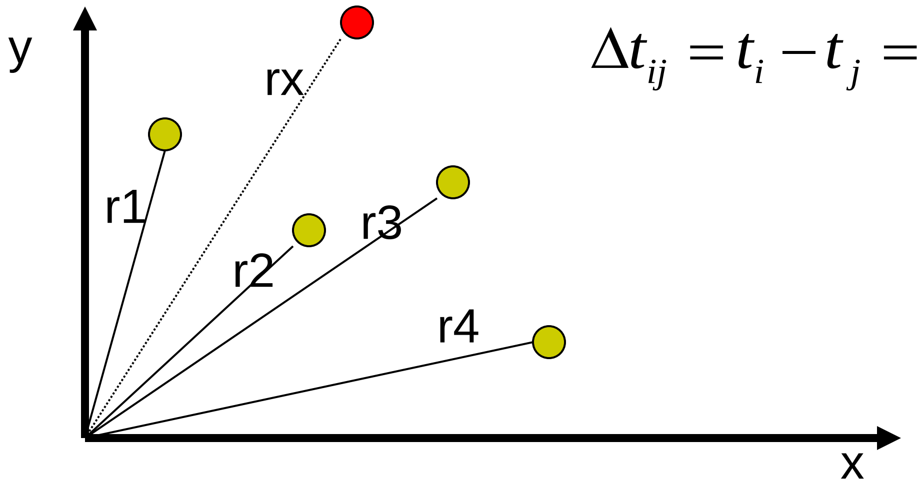
- Measures the difference between sending and receiving time
- Time should be accurately synchronized
  - Adds to the cost of sensors
  - Needs a highly accurate clock
  - Increase the complexity of the sensor network
- This disadvantage makes it a less attractive option than measuring roundtrip time in WSNs.

Roundtrip Propagation Time Measurements

- Measures the difference between the sending time and receiving time of returned signal at the original sensor.
- There is no synchronization problem
- The major error source is the delay required for handling the signal in the second sensor
- This internal delay is either known via a priori calibration, or measured and sent to the first sensor to be subtracted.

Time-Difference-of-Arrival (TDOA) Measurements

- To estimate the location of the transmitter.
  - Using TDOA measurements of the transmitter's signal at a number of receivers with known location



$$\Delta t_{ij} = t_i - t_j = \frac{1}{c}\left(\|r_i - r_x\| - \|r_j - r_x\|\right)$$

Distance Estimation Via RSS Measurements

- It is based on a standard feature found in most wireless devices, a Received Signal Strength Indicator (RSSI).
- It requires no additional hardware
- In free space the received power is related to the distance through the Friis equation

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

  - Pt is the transmitted power,
  - Gt is the transmitter antenna gain,
  - Gr is the receiver antenna gain
  - λ is the wavelength of the transmitter signal in meters.

Problems

- The free-space model however is an over-idealization
- The propagation of a signal is affected by:
  - Reflection, diffraction and scattering.
  - These effects are environment dependent:
    - (indoors, outdoors, rain, buildings, etc.)

Non Free-Space Model

$$P_r(d) = P_0(d_0) - 10 n_p \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

a known reference power value at a reference distance d0 from the transmitter

a zero mean Gaussian distributed random variable

the path loss exponent that measures the rate at which the RSS decreases with distance

Measurement Techniques

- Angle-of-arrival measurements (AOA)
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  - use of the receiver antenna's phase response.
- Distance related measurements
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Received Signal Strength (RSS) Profiling Measurements

- Construct a form of map of the signal strength behavior in the coverage area.
- The map is obtained:
  - Offline by a priori measurements
  - Online using sniffing devices deployed at known locations.
- They have been mainly used for location estimation in WLANs

Received signal strength (RSS) Profiling Measurements

- Different nodes:
  - Anchor nodes
  - Non-anchor nodes,
  - A large number of sample points (e.g., sniffing devices)
- At each sample point, a vector of signal strengths is obtained
  - jth entry corresponding to the jth anchor's transmitted signal.
- The collection of all these vectors provides a map of the whole region
- The collection constitutes the RSS model
- It is unique with respect to the anchor locations and the environment
- The model is stored in a central location.
- A non-anchor node can estimate its location using the RSS measurements from anchors.

Non Line-of-Sight (NLOS) Error

- A common problem in many localization techniques
- NLOS errors between two sensors can arise when:
  - The line-of-sight between them is obstructed , perhaps by a building,
  - The line-of sight measurements are contaminated by reflected and/or diffracted signals.
- NLOS error mitigation techniques:
  - Assume that NLOS corrupted measurements only constitute a small fraction of the total measurements.
  - A typical approach is to assume that the measurement error has a Gaussian distribution

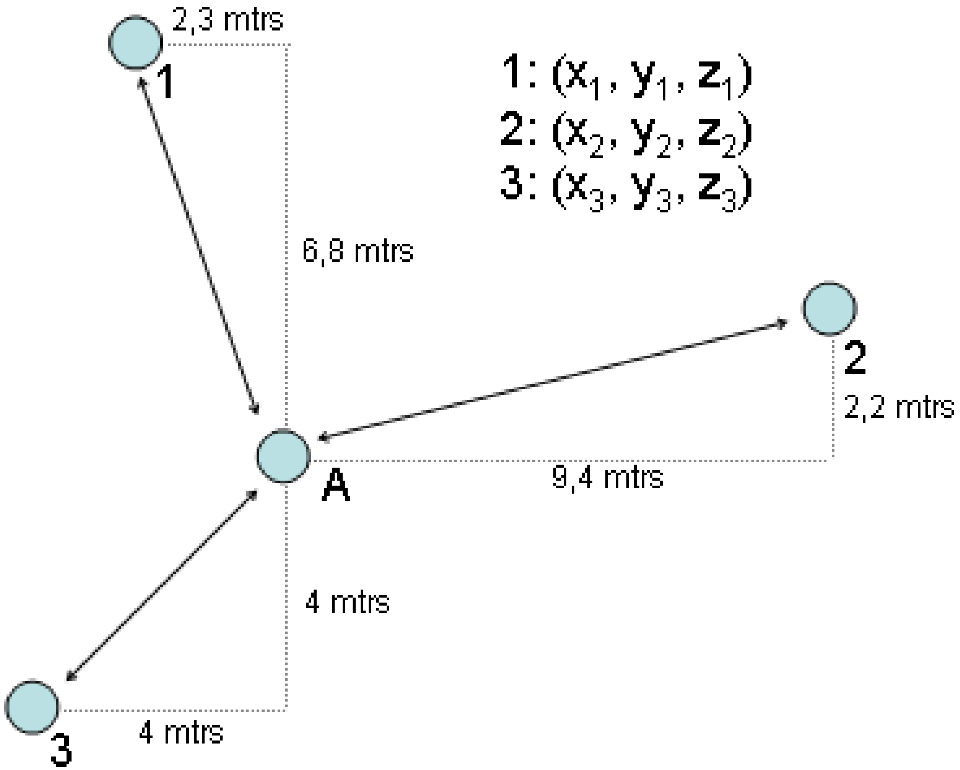
Localization Algorithms

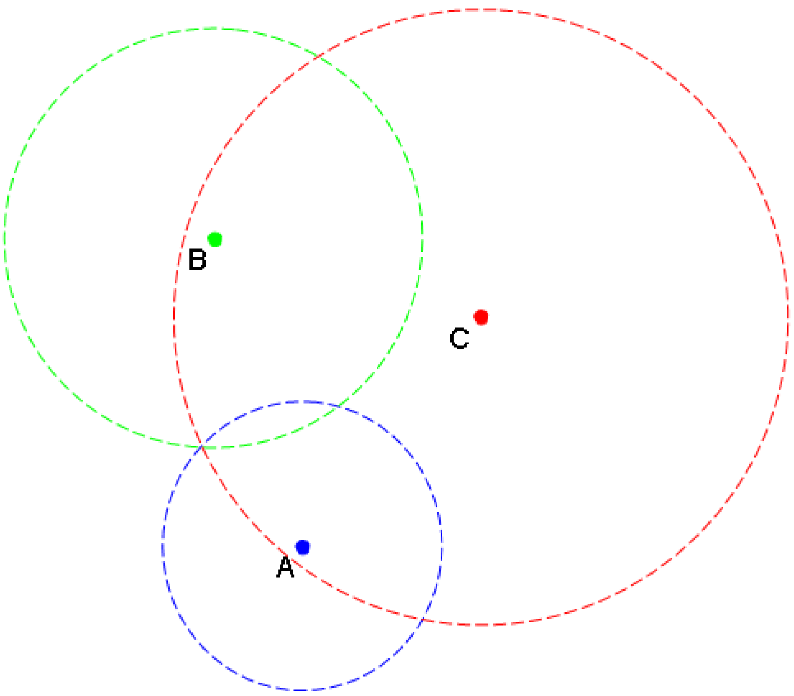
- One-hop localization
  - The non anchor node to be localized is the one-hop neighbor of a sufficient number of anchors
- Connectivity based multi-hop localization algorithms
  - The non-anchor nodes are not necessarily the one-hop neighbors of the anchors.
  - Some time they are called ‘‘range free’’ localization
    - Do not rely on any of the measurement techniques
    - Instead they use the connectivity information to estimate the locations of the non anchor nodes.

One-hop Localization Techniques

- Given:
  - Three points with known positions
  - Distances to all three of them
- Lateration:
  - Position can be determined by intersecting three circle centered in the points with radius the known distances

Lateration as Localization Technique





Trilateration

- Assuming distances to three points with known location are exactly given
- Solve system of equations (Pythagoras!)
  - (x_i, y_i) : coordinates of ***anchor point*** i, r_i distance to anchor i
  - (x_u, y_u) : unknown coordinates of node

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

  - Subtracting eq. 3 from 1 & 2:

$$(x_1 - x_u)^2 - (x_3 - x_u)^2 + (y_1 - y_u)^2 - (y_3 - y_u)^2 = r_1^2 - r_3^2$$
$$(x_2 - x_u)^2 - (x_2 - x_u)^2 + (y_2 - y_u)^2 - (y_2 - y_u)^2 = r_2^2 - r_3^2.$$

  - Rearranging terms gives a linear equation in (x_u, y_u)!

$$2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$
$$2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_2^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$$

Trilateration as Matrix Equation

- Rewriting as a matrix equation:

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

- Example: $(x_1, y_1) = (2,1)$, $(x_2, y_2) = (5,4)$, $(x_3, y_3) = (8,2)$,
  $r_1 = 10^{0.5}$, $r_2 = 2$, $r_3 = 3$

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

! $(x_u,y_u) = (5,2)$

Lateration

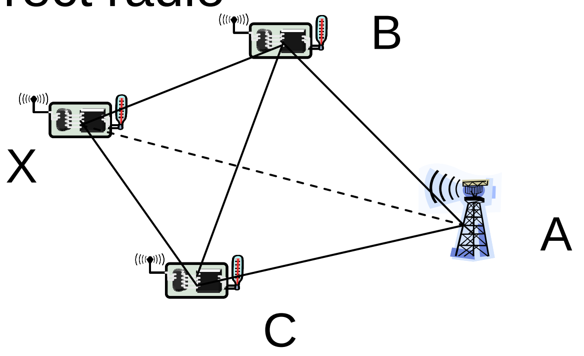
- The concept can be easily applied to multihop networks
- The method as such is not too useful:
  - Imprecise position information
  - Imprecise distance estimates
  - The three circles usually do not intersect in a point (or at all!)
- Several algorithms developed on this simple idea

Connectivity Based Multi-hop Localization Algorithms

- A sensor being in the transmission range of another sensor defines a proximity constraint between both sensors, which can be exploited for localization.

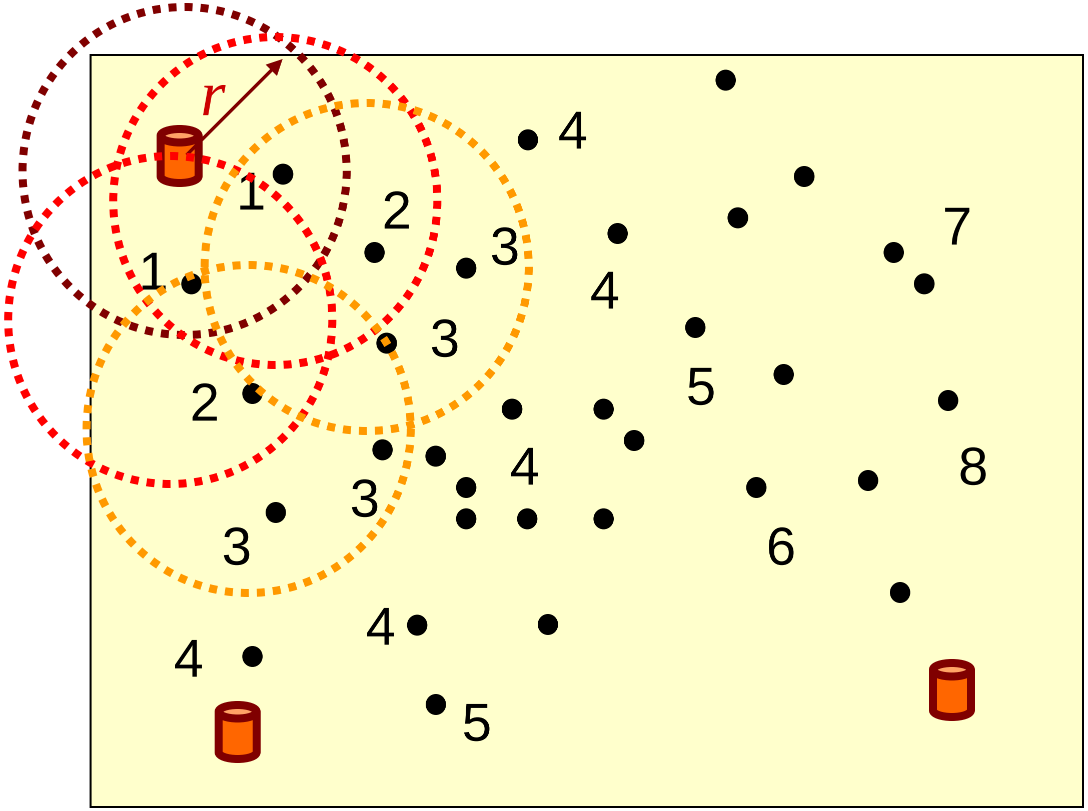
Multihop Range Estimation

- How to estimate range to a node to which no direct radio communication exists?
  - No RSSI, TDoA, …
  - But: Multihop communication is possible



- Idea 1:
  - Count number of hops, assume length of one hop is known (***DV-Hop***)
  - Start by counting hops between anchors, divide known distance
- Idea 2:
  - If range estimates between neighbors exist, use them to improve total length of route estimation in previous method (***DV-Distance***)

Hop-Count Techniques (DV-HOP)



Works well with a few, well-located seeds and regular, static node distribution. Works poorly if nodes move or are unevenly distributed.

Distance-based Multi-hop Localization Algorithms

- Use of inter-sensor distance measurements in a sensor network to locate the entire network.
- Two main classes:
  - Centralized algorithms
    - Use a single central processor to collect all data
    - Produce a map of the entire sensor network
  - Distributed algorithms
    - Rely on self-localization of each node using
      - the distances the node measures
      - the local information it collects from its neighbors.

Centralized Algorithms

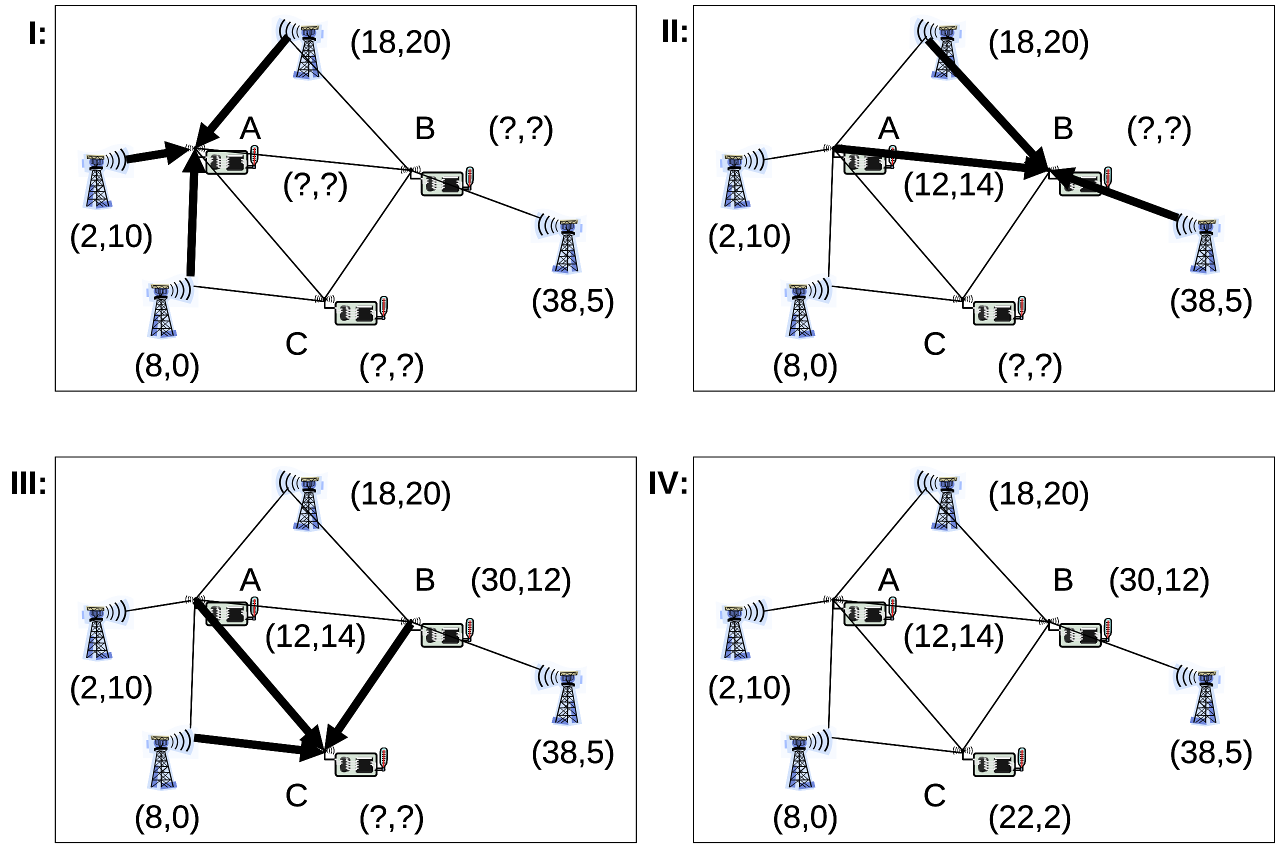
- In certain networks a centralized information architecture already exists, such as:
  - Road traffic monitoring and control
  - Environmental monitoring
  - Health monitoring
  - Precision agriculture monitoring networks
- The measurement data of all the nodes in the network are collected in a central processor unit.
- In such a network, it is convenient to use a centralized localization scheme.

Centralized Algorithms Characteristics

- All the data is collected at a central point and a global map is computed at once
- Advantages:
  - High quality solutions (in terms of the average distance error)
  - Global maps available
- Disadvantages:
  - Data needs to travel to a central point
  - High computation power required
  - Methods usually do not scale with the network size

Distributed Algorithm (Iterative Multilateration)

- Assume some nodes can hear at least three anchors (to perform triangulation), but not all
- Idea: let more and more nodes compute position estimates, spread position knowledge in the network
  - Problem: Errors accumulate



Distributed Algorithms

- These methods allow nodes to compute their position by communicating to their neighbors only
- Advantages:
  - No need of global knowledge
  - Simple methods, majority of algorithms fit the hardware
  - Lower communication overhead
- Disadvantages
  - High number of anchors needed
  - Not all the nodes can compute their position
  - The resulting positions are less precise

Centralized Versus Distributed Algorithms

- They can be compared from perspectives of:
  - Location estimation accuracy
  - Implementation and computation issues
  - Energy consumption
- Decentralized localization is strictly harder than centralized
  - Any algorithm for decentralized localization can always be applied to centralized problems, but not the reverse.

Centralized Versus Distributed Algorithms

- Advantages centralized algorithms:
  - Are likely to provide more accurate location estimates than distributed algorithms.
  - Suffer from the scalability problem
  - Generally are not feasible to be implemented for large scale sensor networks.
- Disadvantages of centralized algorithms:
  - Higher computational complexity
  - Lower reliability due to accumulated information inaccuracies/losses caused by multi-hop transmission over a wireless network.

Centralized Versus Distributed Algorithms

- Distributed algorithms:
  - More difficult to design
  - Optimal distribution of the computation of a centralized algorithm in a distributed implementation in general is an unsolved research problem.
  - Error propagation is another potential problem in distributed algorithms.
  - Generally require multiple iterations to arrive a stable solution

Energy Consumption

- Centralized algorithms require data to be sent over multiple hops to a central processor.
- Distributed algorithms require only local information exchange between neighboring nodes
  - Many such local exchanges may be required, depending on the number of iterations needed to arrive at a stable solution.
- If in a given sensor network and distributed algorithm, the average number of hops to the central processor exceeds the necessary number of iterations, then the distributed algorithm will be more energy-efficient than a typical centralized algorithm.