NODE AND NETWORK MANAGEMENT

LOCALIZATION

OUTLINES

- Ranging Techniques
- Types of Localization Techniques
- Range-based Localization
- Range-free Localization
- Event-driven Localization

OVERVIEW

- Without knowledge of location of a sensor, the information produced by such sensor is of limited use
  - location of sensed events in the physical world
  - location-aware services
  - location often primary sensor information (supply chain management, surveillance)
  - object tracking
  - protocols based on geographic information (routing)
  - coverage area management
- Location often not known a priori, therefore, localization is the task of determining the position (e.g., coordinates) of a sensor or the spatial relationships among objects

OVERVIEW

- Global position
  - position within general global reference frame
  - Global Positioning System or GPS (longitudes, latitudes)
  - Universal Transverse Mercator or UTM (zones and latitude bands)
- Relative position
  - based on arbitrary coordinate systems and reference frames
  - distances between sensors (no relationship to global coordinates)
- Accuracy versus precision
  - GPS: true within 10m for 90% of all measurements
  - accuracy: 10m ("how close is the reading to the ground truth?")
  - precision: 90% ("how consistent are the readings?")

RANGING TECHNIQUES

- Time of Arrival (ToA, time of flight)
  - ❑ distance between sender and receiver of a signal can be determined using the measured signal propagation time and known signal velocity
  - ❑ sound waves: 343m/s, i.e., approx. 30ms to travel 10m
  - ❑ radio signals: 300km/s, i.e., approx. 30ns to travel 10m

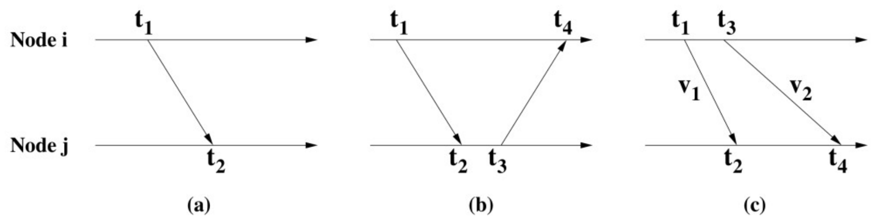
- One-way ToA
  - ❑ one-way propagation of signal
  - ❑ requires highly accurate synchronization of sender and receiver clocks

$$dist_{ij} = (t_2 - t_1) * v$$

- Two-way ToA
  - ❑ round-trip time of signal is measured at sender device
  - ❑ third message if receiver wants to know the distance

$$dist_{ij} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} * v$$

RANGING TECHNIQUES



- Time Difference of Arrival (TDoA)
  - ❑ two signals with different velocities
  - ❑ example: radio signal (sent at t1 and received at t2), followed by acoustic signal (sent at t3=t1+twait and received at t4)

$$dist = (v_1 - v_2) * (t_4 - t_2 - t_{wait})$$

  - ❑ no clock synchronization required
  - ❑ distance measurements can be very accurate □ need for additional hardware

RANGING TECHNIQUES

- Angle of Arrival (AoA)
  - direction of signal propagation
  - typically achieved using an array of antennas or microphones
  - angle between signal and some reference is orientation
  - spatial separation of antennas or microphones leads to differences in arrival times, amplitudes, and phases
  - accuracy can be high (within a few degrees)
  - adds significant hardware cost

RANGING TECHNIQUES

- Received Signal Strength (RSS)
  - signal decays with distance
  - many devices measure signal strength with received signal strength indicator (RSSI)
    - vendor-specific interpretation and representation
    - typical RSSI values are in range of 0..RSSI_Max
    - common values for RSSI_Max: 100, 128, 256
  - in free space, RSS degrades with square of distance
  - expressed by Friis transmission equation

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

  - In practice, the actual attenuation depends on multipath propagation effects, reflections, noise, etc. 🡪 realistic models replace R2 with Rn (n=3..5)

TYPES OF LOCALIZATION TECHNIQUES

- Localization schemes are classified as anchor based or anchor free, centralized or distributed, GPS based or GPS free, fine grained or coarse grained, stationary or mobile sensor nodes, and range based or range free. We will briefly discuss all of these methods.

- Anchor Based and Anchor Free

  In anchor-based mechanisms, the positions of few nodes are known. Unlocalized nodes are localized by these known nodes positions. Accuracy is highly depending on the number of anchor nodes.

  Anchor-free algorithms estimate relative positions of nodes instead of computing absolute node positions.

TYPES OF LOCALIZATION TECHNIQUES

- Centralized and Distributed

  In centralized schemes, all information is passed to one central point or node which is usually called "sink node or base station". Sink node computes position of nodes and forwards information to respected nodes. Computation cost of centralized based algorithm is decreased, and it takes less energy as compared with computation at individual node.

  In distributed schemes, sensors calculate and estimate their positions individually and directly communicate with anchor nodes. There is no clustering in distributed schemes, and every node estimates its own position

TYPES OF LOCALIZATION TECHNIQUES

- GPS Based and GPS Free

  GPS-based schemes are very costly because GPS receiver has to be put on every node. Localization accuracy is very high as well.

  GPS-free algorithms do not use GPS, and they calculate the distance between the nodes relative to local network and are less costly as compared with GPS-based schemes. Some nodes need to be localized through GPS which are called anchor or beacon nodes that initiate the localization process

- Coarse Grained and Fine Grained

  Fine-grained localization schemes result when localization methods use features of received signal strength, while coarse-grained localization schemes result without using received signal strength.

TYPES OF LOCALIZATION TECHNIQUES

- Stationary and Mobile Sensor Nodes

  Localization algorithms are also designed according to field of sensor nodes in which they are deployed. Some nodes are static in nature and are fixed at one place, and the majority applications use static nodes. That is why many localization algorithms are designed for static nodes. Few applications use mobile sensor nodes, for which few mechanisms are designed

- Range-Free and Range-Based Localization

  Range-free methods are distance vector (DV) hop, hop terrain, centroid system, APIT, and gradient algorithm. Range-free methods use radio connectivity to communicate between nodes to infer their location. In range-free schemes, distance measurement, angle of arrival, and special hardware are not used

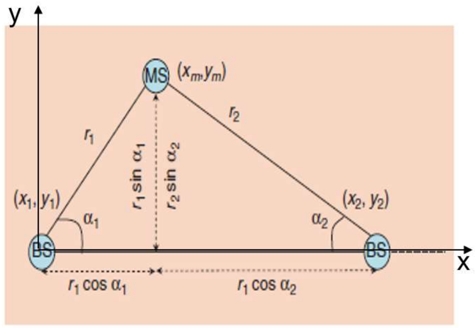
  Range-based schemes are distance-estimation- and angle-estimation-based techniques. Important techniques used in range-based localization are received signal strength indication (RSSI), angle of arrival (AOA), time difference of arrival (TDOA), and time of arrival (TOA)

TRIANGULATION

- **Triangulation** is the process of determining the location of a point by measuring only angles to it from known points at either end of a fixed baseline by using trigonometry, rather than measuring distances to the point directly as in trilateration.
- The point can then be fixed as the third point of a triangle with one known side and two known angles.
- In this approach, information about angles (using AoA) is used instead of distances. Position computation can be done remotely or by the node itself (auto-localization); the latter is more common in WSN.
- In this last case, depicted in (b) at least three reference nodes are required. The unknown node estimates its angle to each of the three reference nodes and, based on these angles and the positions of the reference nodes (which form a triangle), computes its own position using simple trigonometrically relationships.

TRIANGULATION

- Example of range-based localization
- Uses the geometric properties of triangles to estimate location
- Relies on angle (bearing) measurements
- Minimum of two bearing lines (and the locations of anchor nodes or the distance between them) are needed for two-dimensional space
- AoA to compute the angles.
- The number of BSs needed for the location process is less.
- Compute the linear least-square solution.
- Assuming $(x_1,y_1)=(0,0)$ and the x axis defined by the two beacon nodes we have:



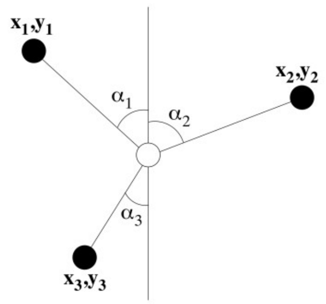
$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \begin{bmatrix} r_1 \cos \alpha_1 \\ r_1 \sin \alpha_1 \end{bmatrix}$$

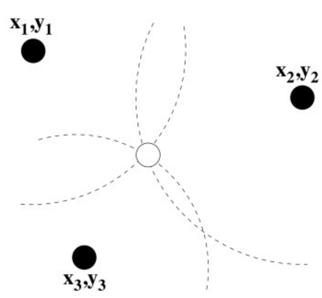
and

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \begin{bmatrix} x_2 \\ 0 \end{bmatrix} + \begin{bmatrix} r_2 \cos \alpha_2 \\ r_2 \sin \alpha_2 \end{bmatrix}$$

TRIALTERATION

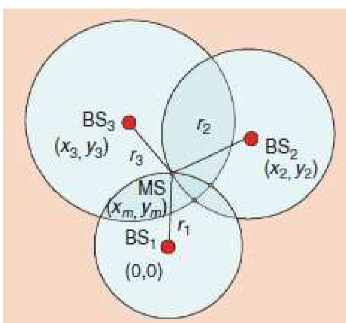
- Localization based on measured distances between a node and a number of anchor points with known locations.
- Basic concept: given the distance to an anchor, it is known that the node must be along the circumference of a circle centered at anchor and a radius equal to the node-anchor distance.
- In two-dimensional space, at least three non-collinear anchors are needed and in three-dimensional space, at least four non-coplanar anchors are needed





TRIALTERATION

- Distance measured: RSSI, ToA, TDoA
- Requires at least 3 BNs in 2D, and 4 BNs in 3D..
- Compute the linear least-squares solution
- Multilateration if more than three beacons are used to estimate the sensor's position



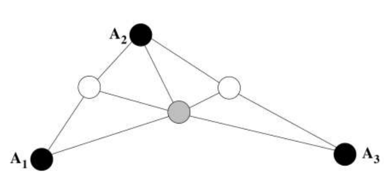
$$r_1^2 = x_m^2 + y_m^2$$
$$r_2^2 = (x_2 - x_m)^2 + (y_2 - y_m)^2$$
$$r_3^2 = (x_3 - x_m)^2 + (y_3 - y_m)^2$$

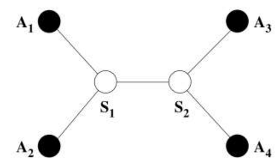
ITERATIVE/COLLABORATIVE MULTILATERATION

- Problem: what if node does not have at least three neighboring anchors?

- Solution: once a node has determined its position, it becomes an anchor Iterative Multilateration:
  - repeats until all nodes have been localized
  - error accumulates with each iteration

- Collaborative Multilateration:
  - goal: construct a graph of participating nodes, i.e., nodes that are anchors or have at least three participating neighbors
  - node then tries to estimate its position by solving the corresponding system of over constrained quadratic equations relating the distances among the node and its neighbors





GPS BASED LOCALIZATION

- Global Positioning System
  - most widely publicized location-sensing system
  - provides lateration framework for determining geographic positions
  - originally established as NAVSTAR (Navigation Satellite Timing and Ranging)
  - only fully operational global navigation satellite system (GNSS)
  - consists of at least 24 satellites orbiting at approx. 11,000 miles
  - started in 1973, fully operational in 1995

- Two levels of service:
  - Standard Positioning Service (SPS)
    - available to all users, no restrictions or direct charge
    - high-quality receivers have accuracies of 3m and better horizontally

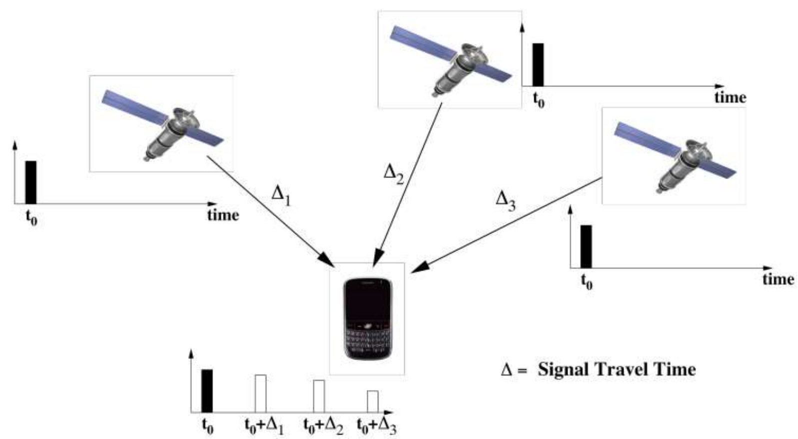
  - Precise Positioning Service (PPS)
    - used by US and Allied military users
    - uses two signals to reduce transmission errors

GPS BASED LOCALIZATION

- Satellites are uniformly distributed in six orbits (4 satellites per orbit)
- Satellites circle earth twice a day at approx. 7000 miles/hour
- At least 8 satellites can be seen simultaneously from almost anywhere
- Each satellite broadcasts coded radio waves (pseudorandom code), containing
  - ❑ identity of satellite
  - ❑ location of satellite
  - ❑ the satellite's status
  - ❑ data and time when signal was sent
- Six monitor stations constantly receive satellite data and forward data to a master control station (MCS)
- MCS is located near Colorado Springs, Colorado
- MCS uses the data from monitor stations to compute corrections to the satellites' orbital and clock information which are sent back to the satellites

GPS BASED LOCALIZATION

- Satellites and receivers use accurate and synchronized clocks
- Receiver compares generated code with received code to determine
  - ❑ the actual code generation time of the satellite
  - ❑ time difference Δ between code generation time and current time
  - ❑ Δ expresses the travel time of the code from satellite to receiver



GPS BASED LOCALIZATION

- Radio waves travel at the speed of light (approx. 186,000 miles/second)
- With known Δ, the distance can be determined
- Receiver knows that it is located somewhere on a sphere centered on the satellite with a radius equal to this distance
- With three satellites, the location can be narrowed down to two points
  - typically one of these two points can be eliminated easily

GPS BASED LOCALIZATION

- With four satellites, accurate localization is possible
  - accurate positioning relies on accurate timing
  - receiver clocks are much less accurate than atomic GPS clocks
  - small timing errors lead to large position errors
    - example: clock error of 1ms translates to a position error of 300km
  - fourth sphere would ideally intersect with all three other spheres in one exact location
  - spheres too large: reduce them by adjusting the clock (moving it forward)
  - spheres too small: increase them by adjusting the clock (moving it backward

GPS BASED LOCALIZATION

- Most GPS receivers today can achieve good accuracy (e.g., 10m or less)

- Additional advanced techniques can be used to further improve accuracy:
  - example: Differential GPS (DGPS)
    - relies on land-based receivers with exactly known locations
    - they receive signals, compute correction factors, and broadcast them to GPS receivers
    - GPS receivers correct their own measurements

- GPS in wireless sensor networks
  - prohibitive factors: power consumption, cost, size, need for LOS
  - deployment can be limited to a few (more powerful) nodes
    - used as anchor nodes and reference points for range-free localization techniques

AD HOC POSITIONING SYSTEM (APS)

- Example of a range-free localization approach
  - based on connectivity information instead of distance/angle measurements
  - no additional hardware required (cost-effective)

- APS is a distributed connectivity-based localization algorithm
  - estimates node locations with the support of at least three anchor nodes
    - localization errors can be reduced by increasing the number of anchors
  - uses concept of DV (distance vector), where nodes exchange routing tables with their one-hop neighbors

AD HOC POSITIONING SYSTEM (APS)

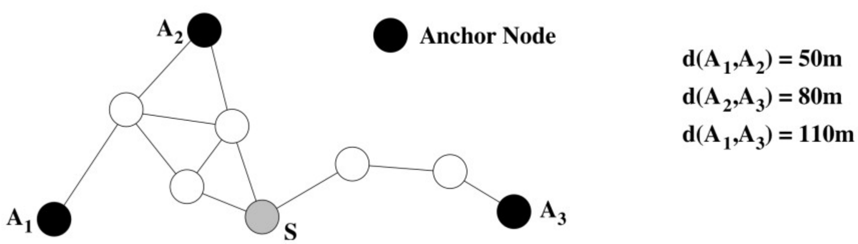
- Most basic scheme of APS: DV-hop
  - each node maintains a table {Xi , Yi , hi } (location of node i and distance in hops between this node and node i)
  - when an anchor obtains distances to other anchors, it determines the average hop length ("correction factor" ci), which is then propagated throughout the network

$$c_i = \frac{\sum \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}}{\sum h_i}$$

  - given the correction factor and the anchor locations, a node can perform trilateration

AD HOC POSITIONING SYSTEM (APS)

- Example with three anchors
  - A1 knows its distance to A2 (50m) and A3 (110m)
  - A1 knows its hop distance to A2 (2) and A3 (6)
  - correction factor: (50+110)/(2+6) = 20 (estimated distance of a hop)
  - corrections are propagated using controlled flooding, i.e., a node only uses one correction factor and ignores subsequently received ones

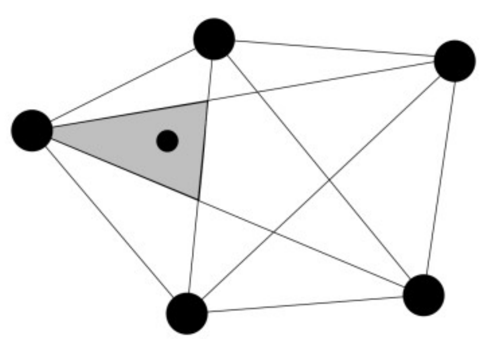


AD HOC POSITIONING SYSTEM (APS)

- Variation of this approach: DV-distance method
  - distances are determined using radio signal strength measurements
  - distances are propagated to other nodes
  - provides finer granularity (not all hops are estimated to be the same size)
  - more sensitive to measurement errors
- Another variation: Euclidean method
  - true Euclidian distances to anchors are used
  - node must have at least two neighbors that have distance measurements to anchors and the distance between the two neighbors is known
  - simple trigonometric relationships are used to determine the distance between node and anchor

APPROXIMATE POINT IN TRIANGULATION (APIT)

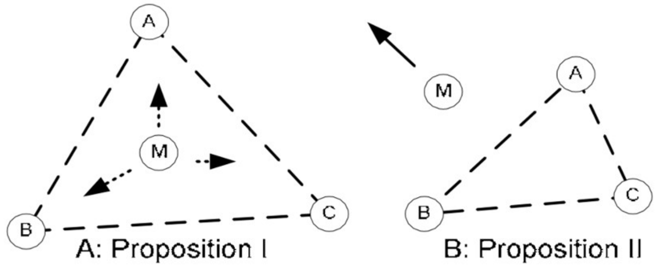
- Example of an area-based range-free localization scheme
- APIT relies on anchor nodes
  - any combination of three anchors forms a triangle
  - a node determines its presence inside or outside a triangle using the Point in Triangulation (PIT) test



APPROXIMATE POINT IN TRIANGULATION (APIT)

Perfect PIT Test

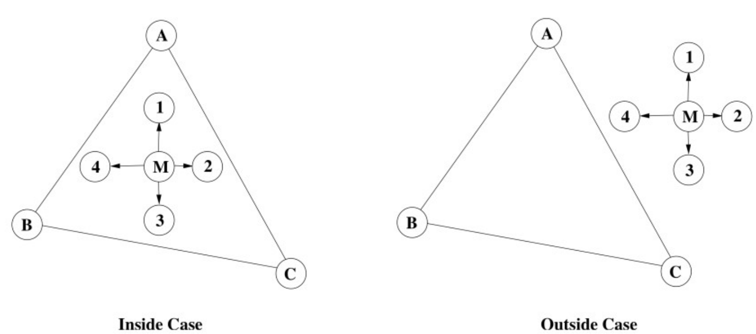
- **Proposition I:** Node M in triangle if: M shifted in any direction New position is nearer/ further from at least one anchor
- **Proposition II:** Node M outside if: M can be shifted in a direction New position is nearer/ further to all three anchors



- This perfect PIT test is infeasible in practice since it would require that a node can be moved in any direction

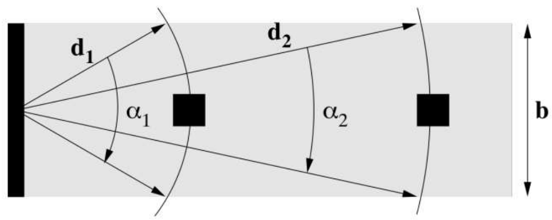
APPROXIMATE POINT IN TRIANGULATION (APIT)

- In dense networks, node movement can be emulated using neighbor information (exchanged via beacons)
  - ❑ signal strength measurements can be used to determine if a node is closer to an anchor or further away
  - ❑ if no neighbor of node M is further from or closer to three anchors A, B, C simultaneously, M can assume that it is inside the triangle



LIGHTHOUSE APPROACH

- Example of an event-driven localization approach
- Requirement: base station with light emitter
- Idealistic light source: emitted beam of light is parallel (constant width b)
- Light source rotates s. t. sensor sees beam of light for t_{beam}



$$d = \frac{b}{2\sin(\alpha/2)} \qquad \alpha = 2\pi \frac{t_{beam}}{t_{turn}}$$

LIGHTHOUSE APPROACH

- Perfectly parallel light beams are hard to realize in practice
- Small beam spreads can result in large localization errors
  - if b=10cm and spread=1°, b'=18.7cm at 5m distance
- Beam width should be large to keep inaccuracies small
- Solution: two laser beams that outline a "virtual" parallel beam
  - only edges of the virtual beam are of interest

MULTISEQUENCE POSITIONING

- MSP works by extracting relative location information from multiple simple one dimensional orderings of sensor nodes
  - event generators at different locations trigger events (e.g., ultrasound signals or laser scans)
  - nodes observe events at different times, leading to node sequence
  - multisequence processing algorithm narrows potential locations for each node
  - distribution-based estimation method can estimate exact locations