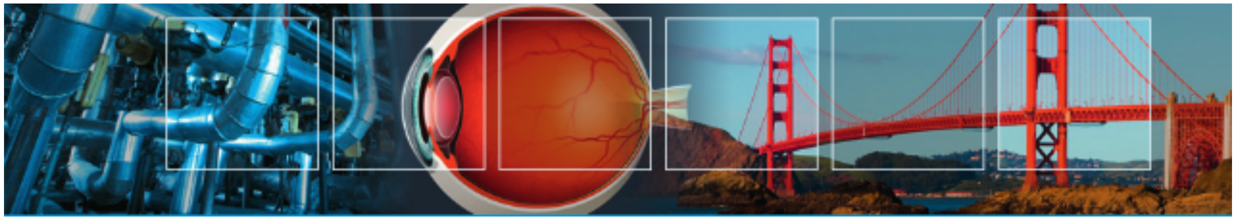
Chapter 10: Localization



Chapter 10: Roadmap

- Ranging techniques
- Range-based localization
- Range-free localization
- Event-driven localization

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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

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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?”)

- Symbolic position information
  - “office 354”
  - “mile marker 17 on Highway 23”

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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

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

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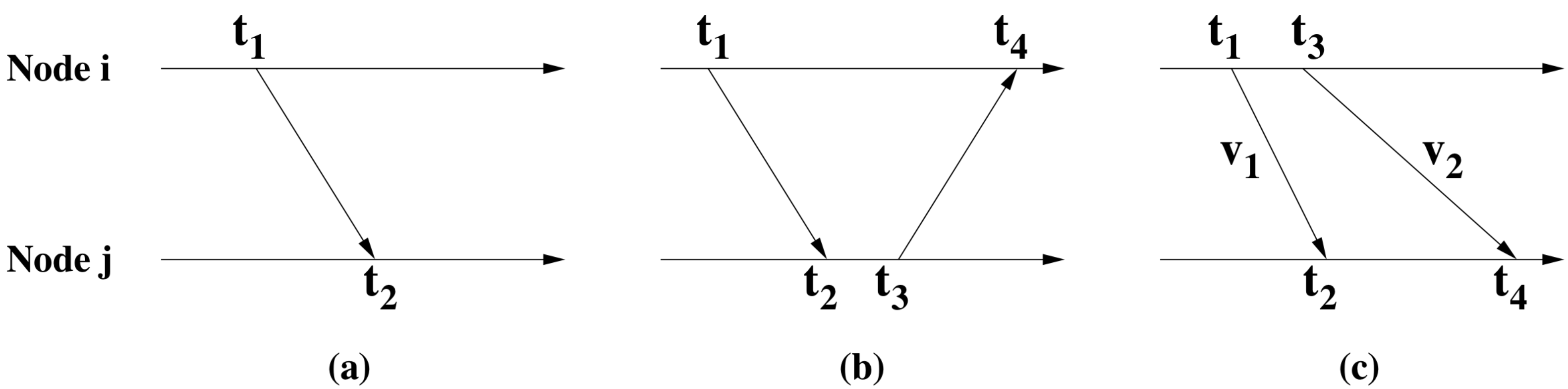
Ranging Techniques



- Time Difference of Arrival (TDoA)
  - two signals with different velocities
  - example: radio signal (sent at t_1 and received at t_2), followed by acoustic signal (sent at $t_3 = t_1 + t_{wait}$ and received at t_4)

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

  - 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

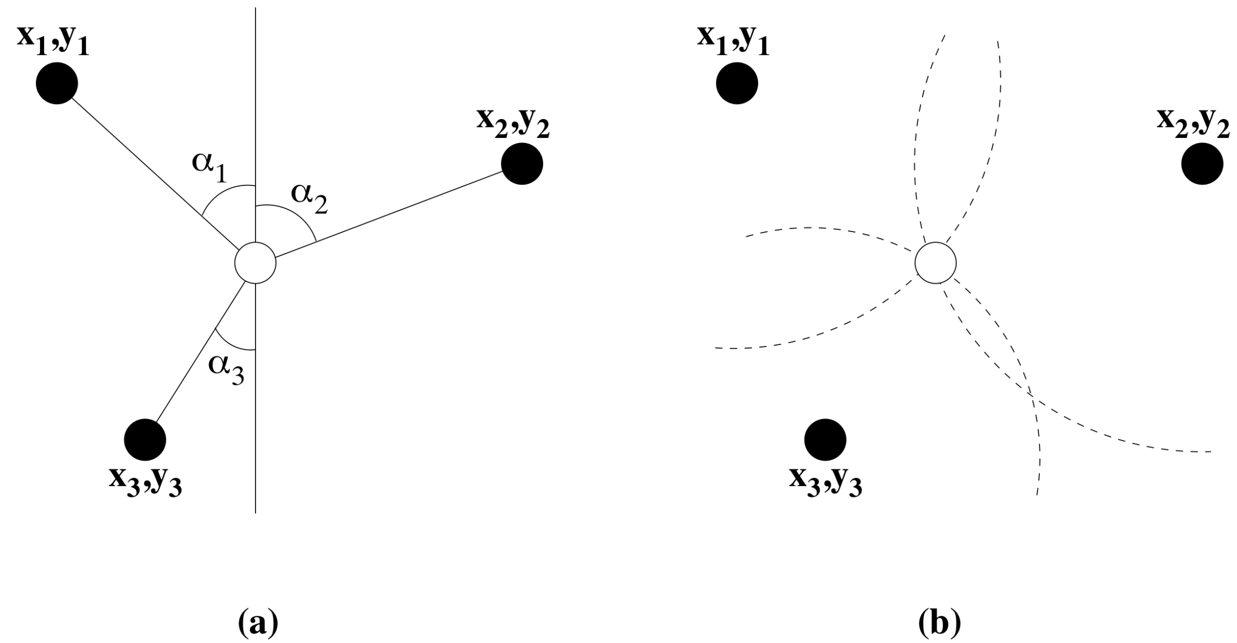
- Received Signal Strength (RSS)
  - signal decays with distance
  - many devices measure signal strength with received signal strength indicator (RSSI)
    - vendor-specific interpretation and representation
    - typical RSSI values are in range of 0..RSSI_Max
    - common values for RSSI_Max: 100, 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 R^2 with R^n (n=3..5)

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



Triangulation

- Unknown receiver location $\mathbf{x_r}=[x_r,y_r]^T$
- Bearing measurements from N anchor points: $\beta=[\beta_1,\ldots,\beta_N]^T$
- Known anchor locations $\mathbf{x_i}=[x_i,y_i]^T$
- Actual (unknown) bearings $\theta(\mathbf{x})=[\theta_1(\mathbf{x}),\ldots, \theta_N(\mathbf{x})]^T$
- Relationship between actual and measured bearings is $\beta=\theta(\mathbf{x_r})+\delta\theta$ with $\delta\theta=[\delta\theta_1,\ldots, \delta\theta_N]^T$ being the Gaussian noise with zero-mean and NxN covariance matrix S=diag $(\sigma_1^2,\ldots,\sigma_N^2)$
- Relationship between bearings of N anchors and their locations:

$$\tan\theta_i(\mathbf{x}) = \frac{y_i - y_r}{x_i - x_r}$$

- Maximum likelihood (ML) estimator of receiver location is then:

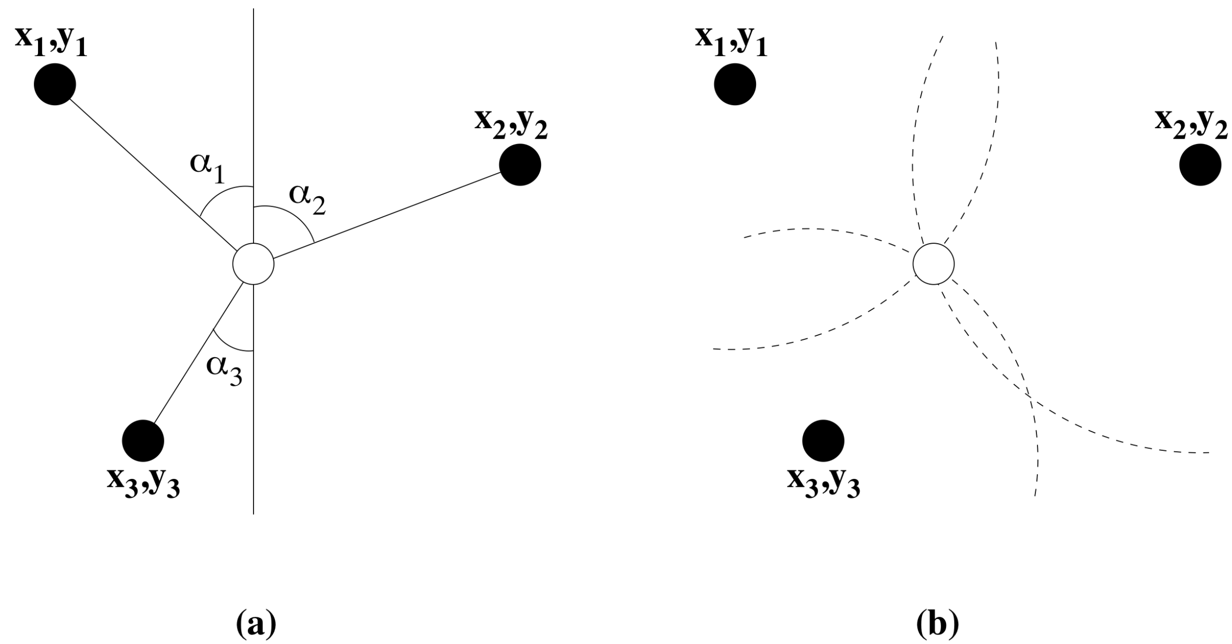
$$\hat{\mathbf{x}}_{\mathbf{r}} = \arg\min \frac{1}{2}[\theta(\hat{\mathbf{x}}_{\mathbf{r}}) - \beta]^T S^{-1}[\theta(\hat{\mathbf{x}}_{\mathbf{r}}) - \beta] = \arg\min \frac{1}{2}\sum_{i=1}^{N}\frac{(\theta_i(\hat{\mathbf{x}}_{\mathbf{r}}) - \beta_i)^2}{\sigma_i^2}$$

- This non-linear least squares minimization can be performed using Newton-Gauss iterations:

$$\hat{\mathbf{x}}_{\mathbf{r,i+1}} = \hat{\mathbf{x}}_{\mathbf{r,i}} + (\theta_x(\hat{\mathbf{x}}_{\mathbf{r,i}})^T S^{-1}\theta_x(\hat{\mathbf{x}}_{\mathbf{r,i}}))^{-1}\theta_x(\hat{\mathbf{x}}_{\mathbf{r,i}})^T S^{-1}[\beta - \theta_x(\hat{\mathbf{x}}_{\mathbf{r,i}})]$$

Trilateration

- 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



Trilateration

- n anchor nodes: $\mathbf{x_i}=(x_i,y_i)$ (i=1..n)
- Unknown sensor location $\mathbf{x}=(x,y)$
- Distances between sensor and anchors known (r_i, i=1..n)
- Relationships between anchor/sensor positions and distances (2 dimensions):

$$\begin{bmatrix} (x_1-x)^2+(y_1-y)^2 \\ (x_2-x)^2+(y_2-y)^2 \\ \vdots \\ (x_n-x)^2+(y_n-y)^2 \end{bmatrix} = \begin{bmatrix} r_1^2 \\ r_2^2 \\ \vdots \\ r_n^2 \end{bmatrix}$$

- This can be represented as $A\mathbf{x}=b$ with:

$$A = \begin{bmatrix} 2(x_n-x_1) & 2(y_n-y_1) \\ 2(x_n-x_2) & 2(y_n-y_2) \\ \vdots & \vdots \\ 2(x_n-x_{n-1}) & 2(y_n-y_{n-1}) \end{bmatrix} \qquad b = \begin{bmatrix} r_1^2-r_n^2-x_1^2-y_1^2+x_n^2+y_n^2 \\ r_2^2-r_n^2-x_2^2-y_2^2+x_n^2+y_n^2 \\ \vdots \\ r_{n-1}^2-r_n^2-x_{n-1}^2-y_{n-1}^2+x_n^2+y_n^2 \end{bmatrix}$$

Trilateration

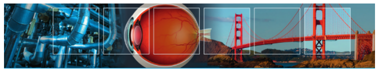
- Based on this least squares system, we can obtain estimation of position (x,y) using $\mathbf{x}=(A^TA)^{-1}A^Tb$
- Anchor positions and distance measurements are inaccurate, therefore, if they are based on Gaussian distributions, we can assign a weight to each equation i:

$$w_i = 1/\sqrt{\sigma^2_{\text{distance}_i} + \sigma^2_{\text{position}_i}} \qquad \sigma^2_{\text{position}_i} = \sigma_{x_i}{}^2 + \sigma_{y_i}{}^2$$

- The least squares system is then again $A\mathbf{x}=b$ with:

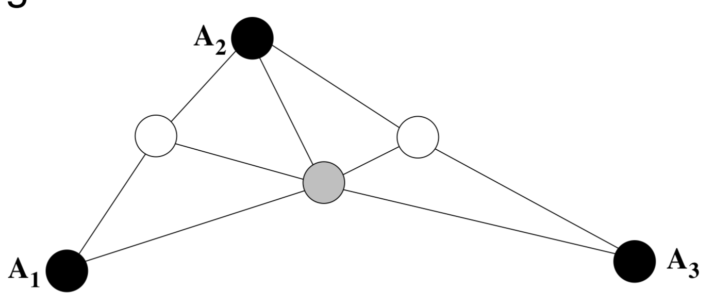
$$A = \begin{bmatrix} 2(x_n - x_1)\times w_1 & 2(y_n - y_1)\times w_1 \\ 2(x_n - x_2)\times w_2 & 2(y_n - y_2)\times w_2 \\ \vdots & \vdots \\ 2(x_n - x_{n-1})\times w_{n-1} & 2(y_n - y_{n-1})\times w_{n-1} \end{bmatrix} \quad b = \begin{bmatrix} (r_1{}^2 - r_n{}^2 - x_1{}^2 - y_1{}^2 + x_n{}^2 + y_n{}^2)\times w_1 \\ (r_2{}^2 - r_n{}^2 - x_2{}^2 - y_2{}^2 + x_n{}^2 + y_n{}^2)\times w_2 \\ \vdots \\ (r_{n-1}{}^2 - r_n{}^2 - x_{n-1}{}^2 - y_{n-1}{}^2 + x_n{}^2 + y_n{}^2)\times w_{n-1} \end{bmatrix}$$

- The covariance matrix of $\mathbf{x}$ is then $Cov_x=(A^TA)^{-1}$



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 overconstrained quadratic equations relating the distances among the node and its neighbors



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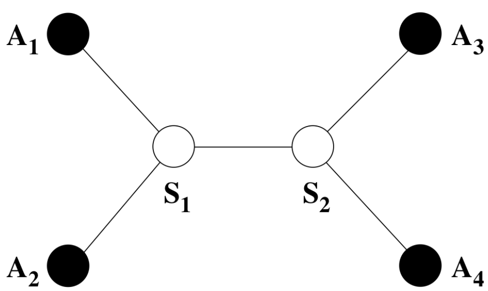


(b)

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

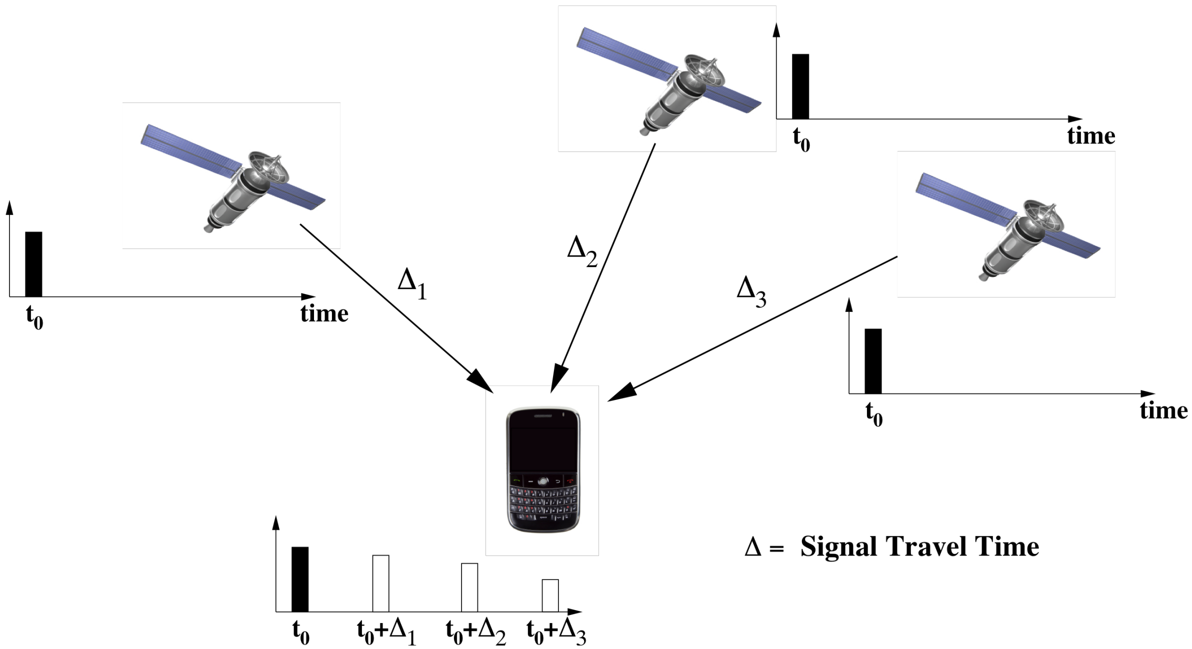
- Two levels of service:
  - Standard Positioning Service (SPS)
    - available to all users, no restrictions or direct charge
    - high-quality receivers have accuracies of 3m and better horizontally
  - Precise Positioning Service (PPS)
    - used by US and Allied military users
    - uses two signals 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
- 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 *{X_i, Y_i, h_i}* (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" c_i), 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

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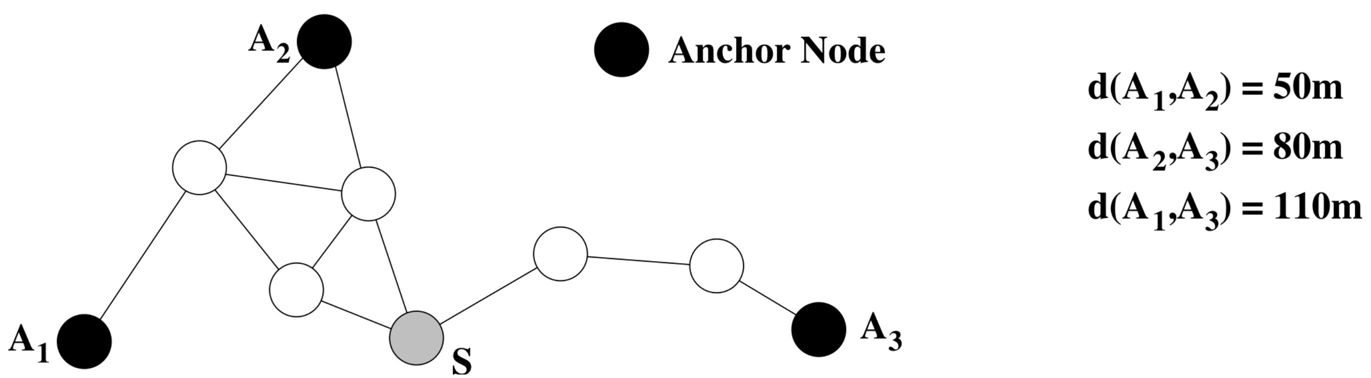
Ad Hoc Positioning System (APS)

- Example with three anchors
  - A_1 knows its distance to A_2 (50m) and A_3 (110m)
  - A_1 knows its hop distance to A_2 (2) and A_3 (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



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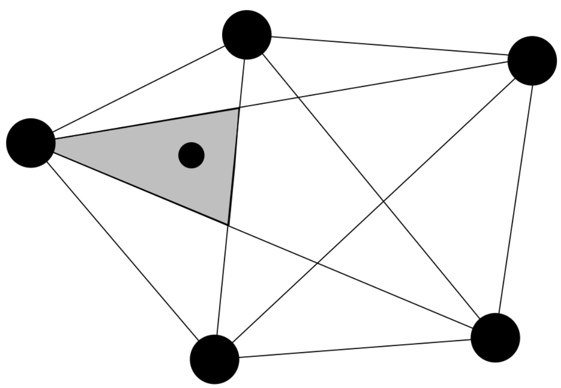
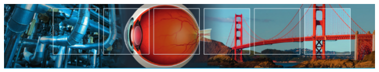
Ad Hoc Positioning System (APS)

- 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

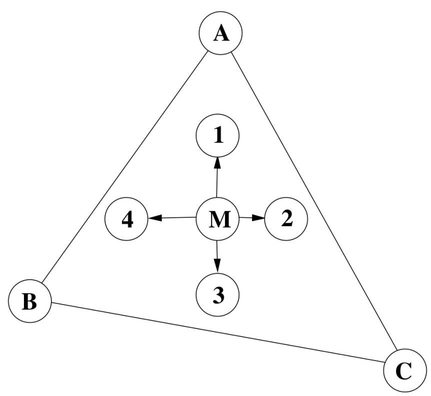
- Example of an area-based range-free localization scheme
- APIT relies on anchor nodes
  - any combination of three anchors forms a triangle
  - a node determines its presence inside or outside a triangle using the Point in Triangulation (PIT) test
    - a node M is outside a triangle formed by anchors A, B, and C if there exists a direction such that a point adjacent to M is either further or closer to all points simultaneously; otherwise M is inside



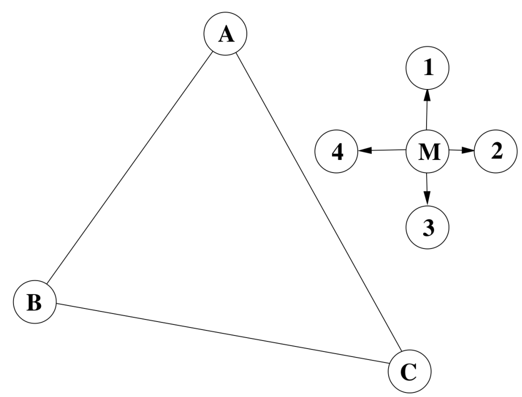


Approximate Point in Triangulation

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



Inside Case



Outside Case

Multidimensional Scaling

- MDS is based on psychometric and psychophysics
- Set of data analysis techniques that display structure of distance-like data as a geometrical picture
- Can be used in centralized localization techniques with powerful central device (base station) collects information from the network, determines the nodes' locations, and propagates this information back into the network
- Network is represented as undirected graph of n nodes, with m ($<n$) anchor nodes (which know their locations), and edges representing the connectivity
- Goal of MDS is to preserve the distance information s. t. the network can be recreated in the multidimensional space
- The result is an arbitrarily rotated and flipped version of the original network layout

Multidimensional Scaling

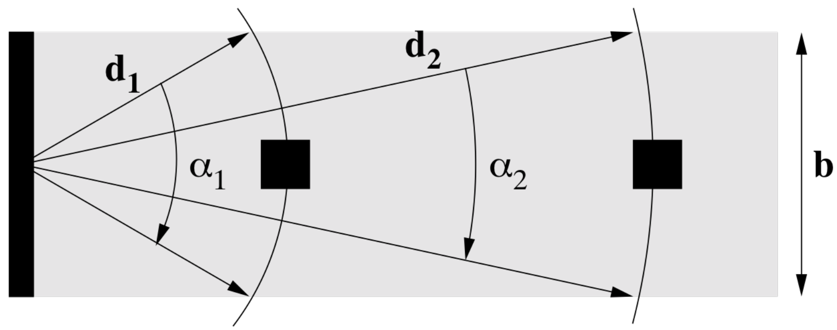
- Classical MDS:
  - simple version, closed form solution for efficient implementation
  - matrix of squared distances between nodes $D^2=c1'+1c'-2SS'$
    - 1 = $nx1$ vector of ones
    - S = similarity matrix, where each row represents the coordinates of point i along m coordinates
    - SS' = scalar product matrix
    - c = vector consisting of diagonal elements of the scalar product matrix
  - Using centering matrix $T=I-11'/n$: $TD^2T=T(c1'+1'c-2SS')T=Tc1'T+T1c'T-T(2B)T$ (where $B=SS'$) and $TD^2T=-T(2B)T$
  - Multiplying both sides with $-1/2$: $B=-1/2TD^2T$
  - B can be decomposed into: $B=\mathcal{Q}\Lambda\mathcal{Q}'=(\mathcal{Q}'\Lambda^{1/2})(\mathcal{Q}\Lambda^{1/2})'=SS'$
  - Once B has been obtained, the coordinates S can be computed by eigendecomposition: $S=\mathcal{Q}\Lambda^{1/2}$

Multidimensional Scaling

- Location method MDS-MAP:
  - construct distance matrix *D*
    - all pairs shortest path algorithm (e.g., Dijkstra's)
    - d_{ij} = distance between nodes *i* and *j*
    - classical MDS is applied to obtain approximate value of the relative coordinate of each node
    - relative coordinates are transformed to absolute coordinates by aligning the estimated relative coordinates of anchors with their absolute coordinates
    - estimates can be further refined using least-squares minimization

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}



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

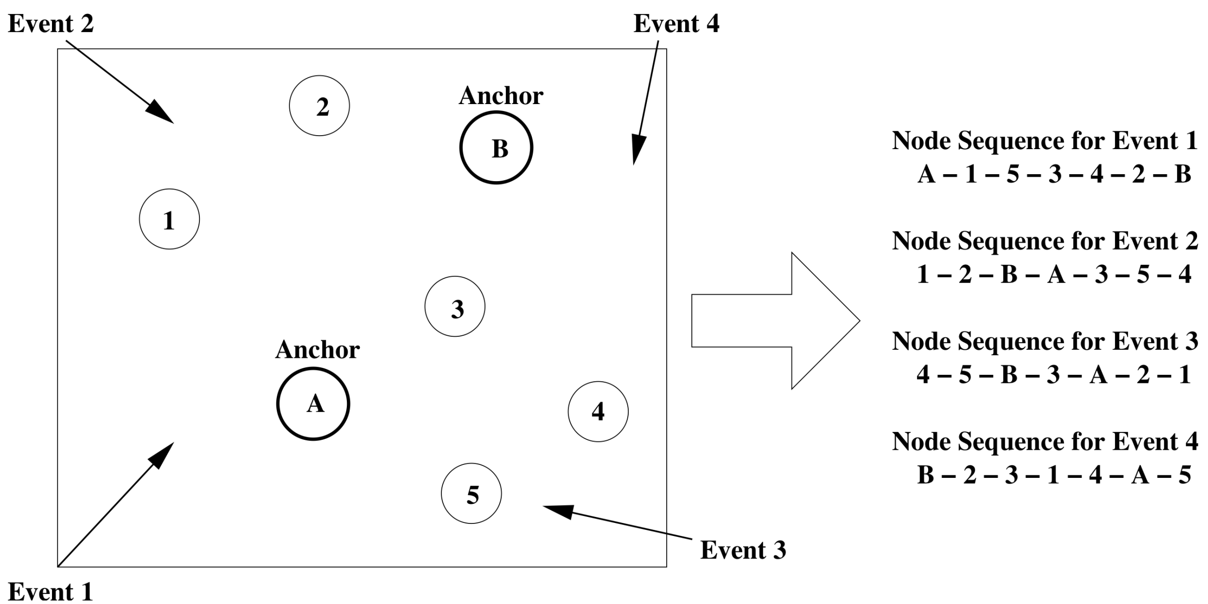
Lighthouse Approach

- 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



Multisequence Positioning

- Each event leads to node sequence
- Multisequence processing algorithm can narrow the potential locations for each node
- Distribution-based estimation method can estimate exact locations