Telecooperation Lab
Prof. Dr. Max Mühlhäuser

TK3: Ubiquitous Computing

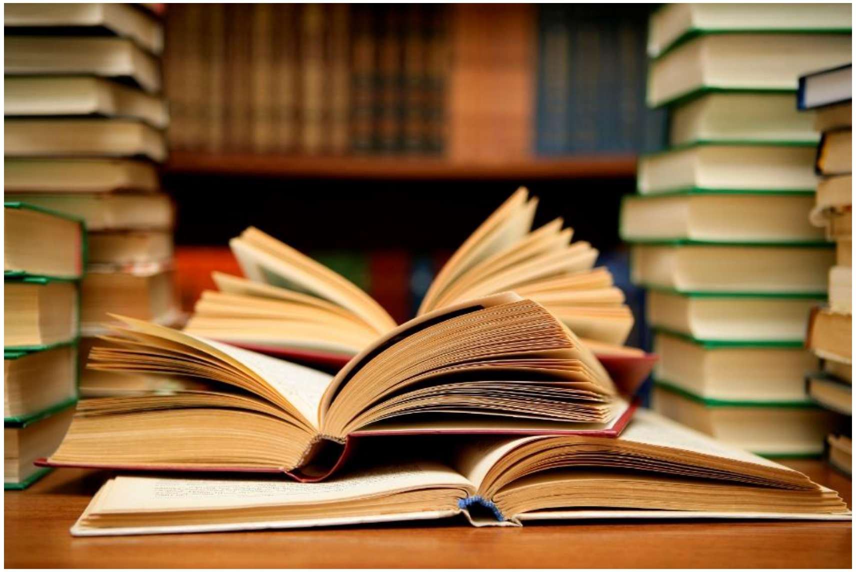
Chapter 3: Context-aware Computing

Part 2: Spatial Context

Lecturer: Dr. Immanuel Schweizer

Sources

- http://cgi.csc.liv.ac.uk/~trp/Teaching_Resources/COMP327/327-Lecture7-ContextAware.pdf



Spatial Context

- Location is an important context (and property of other contexts)
- Sensing data without spatial context?
- Location-aware Services
  - Advertisements
  - Navigation
  - …

Spatial Context

- Positioning system consists of
  - **Navigation sources** - at known locations
  - **Users** – their positions should be determined

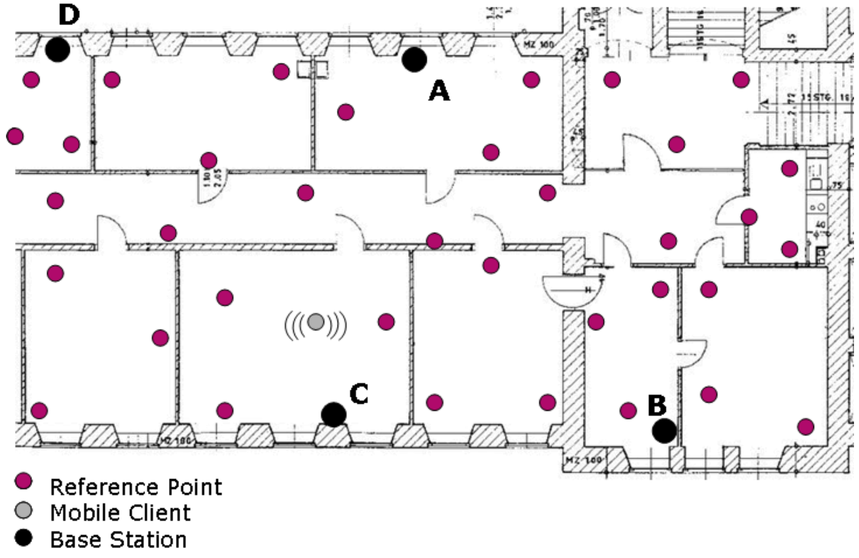
- Information from location sensors can be … / *Positioning Principle*
  - Proximity - Binary information if communication is possible or not
  - Fingerprinting - Quality of communication link
    - Received Signal Strength (RSS)
    - Bit Error Rate (BER)
    - (RFID) read success rate
  - Trilateration - Time of Arrival (TOA)
  - Multilateration - Time Difference of Arrival (TDOA)
  - Triangulation - Angle of Arrival (AOA)

Proximity

- Simplest method
- User‘s position determined as position of closest navigation source
- Example:
  - User carries RFID tag
  - Stationary reader
  - If we can read the tag -> users position := position of navigation source

Fingerprinting (1)

- Location fingerprinting (also called RF pattern matching)
  - Often used in conjunction with RSS
  - Uses an n-dimensional space containing RSS vectors (rss_1, rss_2, … rss_n) of reference points; n = number of navigation sources
- Example:
  - WLAN system with 4 access points (A-D)
  - Reference points described as tuples *(coordinates, RSS vector)* *= ((x,y), (rss_1, … rss_n))*

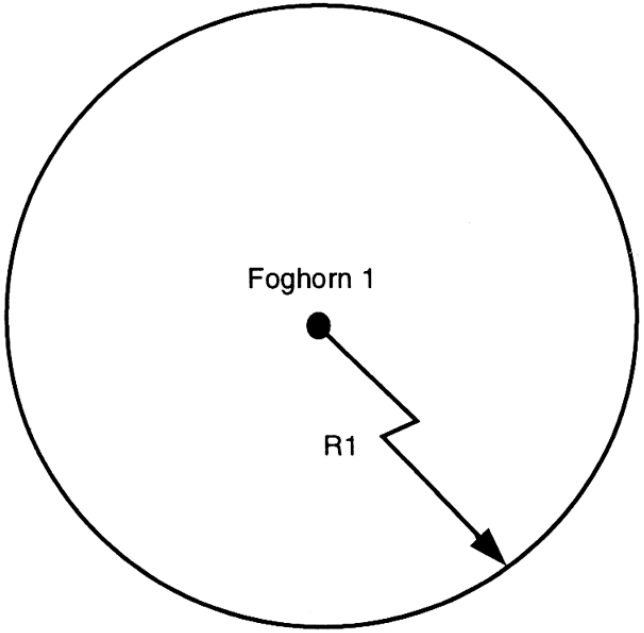


Fingerprinting (2)

- User measures RSS_{user}

- Positioning Algorithms
  - Nearest Neighbor (NN)
    - Find reference point *ref* for which $d(RSS_{user}, RSS_{ref})$ is minimal
    - Assume $pos_{user} := pos_{ref}$
  - Multiple NN (MNN)
    - Find *k* (e.g. three) “closest” (see above) reference points
    - Assume $pos_{user} := \text{center}(pos_{ref1}, pos_{ref2}, \dots pos_{refk})$
  - Interpolation
    - Find three “closest” reference points
    - Use interpolation algorithm on triangle to obtain pos_{user}.

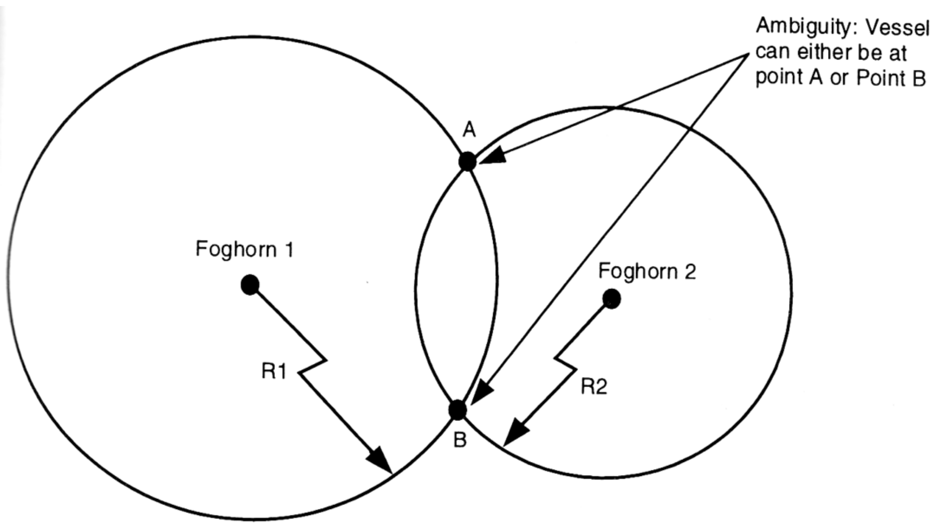
Trilateration

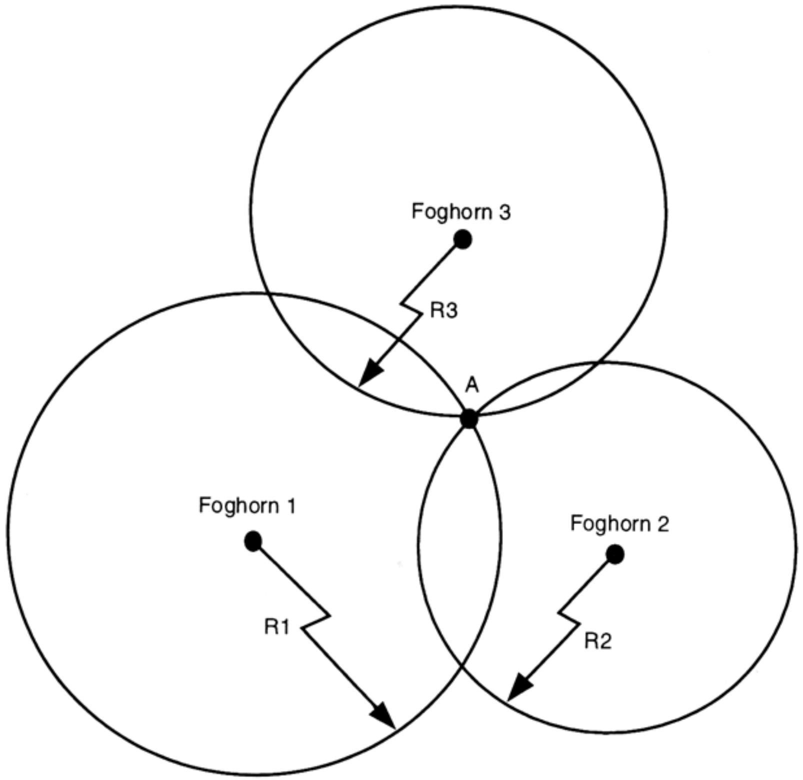


- Time of Arrival (TOA)
  - Foghorn is sounded precisely on the minute mark
  - Mariner has an exact clock and notes elapsed time
  - Distance = propagation time * speed of sound (~335 m/s)

Trilateration

- Two-Dimensional Position Determination





Trilateration

- With three measurements we have:

$$(x - x_1)^2 + (y - y_1)^2 = {r_1}^2 \quad (1.1)$$
$$(x - x_2)^2 + (y - y_2)^2 = {r_2}^2 \quad (1.2)$$
$$(x - x_3)^2 + (y - y_3)^2 = {r_3}^2 \quad (1.3)$$

Setting equations (1.1) and (1.2) equal yields:

$$x = \frac{2y(y_2 - y_1) + {x_1}^2 - {x_2}^2 + {y_1}^2 - {y_2}^2 - {r_1}^2 + {r_2}^2}{2(x_1 - x_2)} \quad (2.1)$$

Similar expressions can be found by intersecting circles 2 and 3, or 1 and 3. Setting equations (1.2) and (1.3) equal yields:

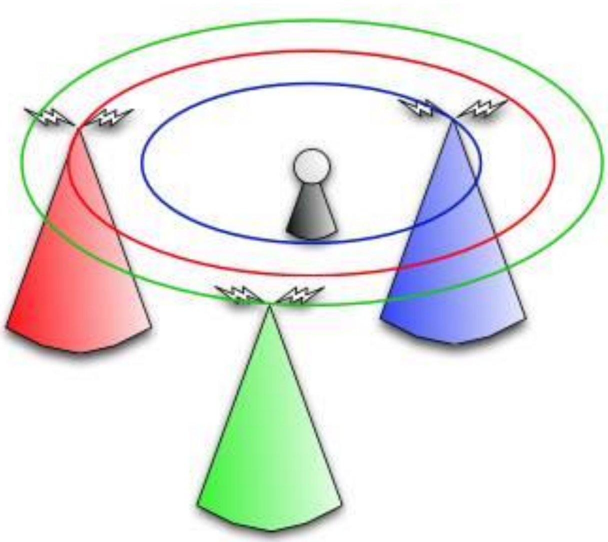
$$x = \frac{2y(y_3 - y_2) + {x_2}^2 - {x_3}^2 + {y_2}^2 - {y_3}^2 - {r_2}^2 + {r_3}^2}{2(x_2 - x_3)} \quad (2.2)$$

Finally, we can combine (2.1) and (2.2) and solve for y:

$$y = \frac{\frac{{x_2}^2 - {x_3}^2 + {y_2}^2 - {y_3}^2 - {r_2}^2 + {r_3}^2}{2(x_2 - x_3)} - \frac{{x_1}^2 - {x_2}^2 + {y_1}^2 - {y_2}^2 - {r_1}^2 + {r_2}^2}{2(x_1 - x_2)}}{\frac{y_2 - y_1}{x_1 - x_2} - \frac{y_3 - y_2}{x_2 - x_3}} \quad (3)$$

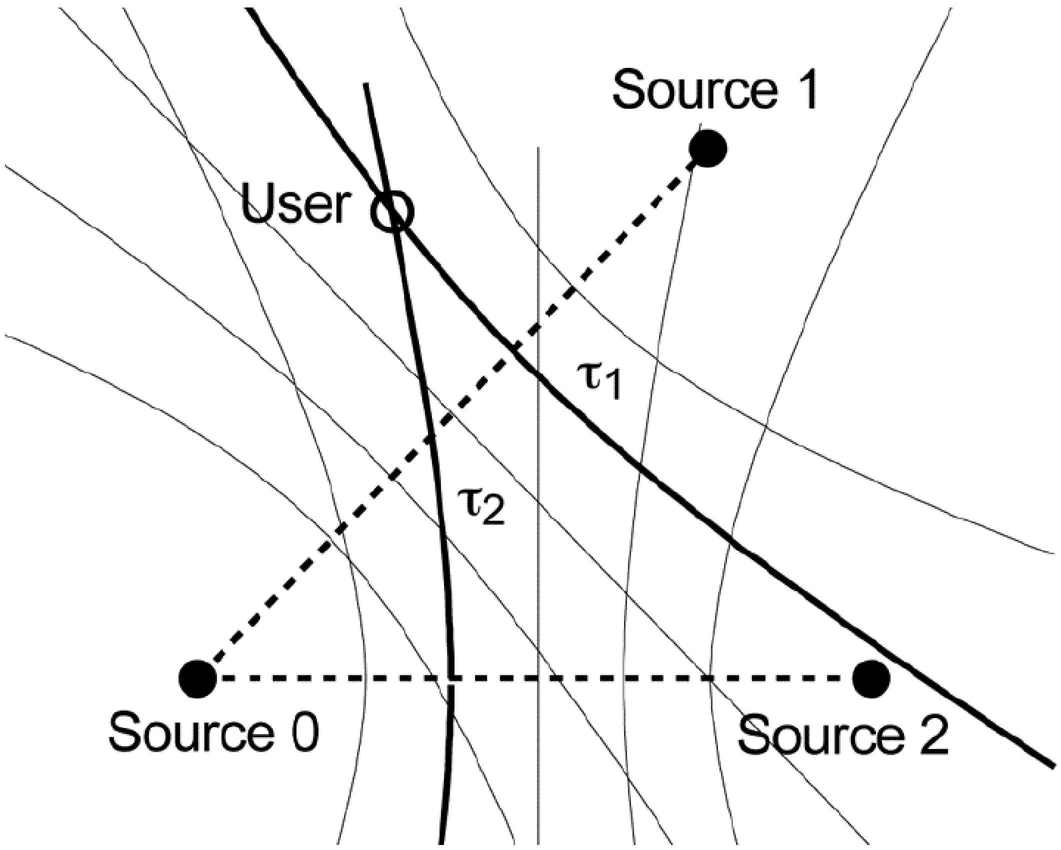
Multilateration

- Time Difference of Arrival (TDOA)
  - Uses propagation delay between mobile terminal and multiple base stations
  - No global time
  - Only time differences are known



Multilateration

- Intersection of two hyperbolas to determine user's 2D position:



Multilateration

The travel time t_i of a signal from a reference station i to the mobile terminal is given by the distance divided by the signal propagation speed v:

$$t_0 = \frac{1}{v}\sqrt{(x-x_0)^2 + (y-y_0)^2} \tag{4.1}$$

$$t_1 = \frac{1}{v}\sqrt{(x-x_1)^2 + (y-y_1)^2} \tag{4.2}$$

$$t_2 = \frac{1}{v}\sqrt{(x-x_2)^2 + (y-y_2)^2} \tag{4.3}$$

If reference station 0 is taken to be at the coordinate system origin, then equation (4.1) can be reduced to:

$$t_0 = \frac{1}{v}\sqrt{x^2 + y^2} \tag{5}$$

The mobile station does not know the absolute values of t_0, t_1, and t_2. It is only able to obtain the time differences:

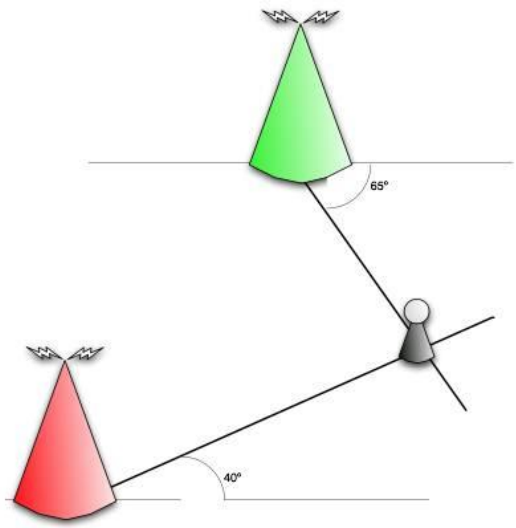
$$\tau_1 = t_1 - t_0 = \frac{1}{v}\left(\sqrt{(x-x_1)^2 + (y-y_1)^2} - \sqrt{x^2 + y^2}\right) \tag{6.1}$$

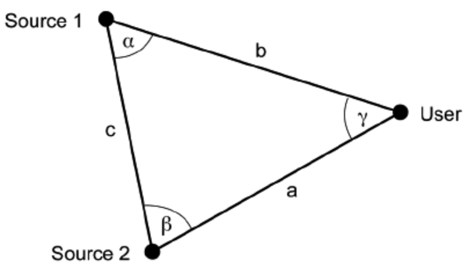
$$\tau_2 = t_2 - t_0 = \frac{1}{v}\left(\sqrt{(x-x_2)^2 + (y-y_2)^2} - \sqrt{x^2 + y^2}\right) \tag{6.2}$$

Equations (6.1) and (6.2) must now be solved for x and y. All other values are known.

Triangulation

- Angle of Arrival (AOA)
  - Base station measures angle to mobile terminal
  - Methods
    - Rotate antenna to highest RSSI value
    - Derive angle from RSSI values of individual antennas in an antenna array (or sector antennas)





$$\gamma = 180^\circ - \alpha - \beta$$

$$a = c\,\frac{\sin\alpha}{\sin\gamma}$$

$$b = c\,\frac{\sin\beta}{\sin\gamma}$$

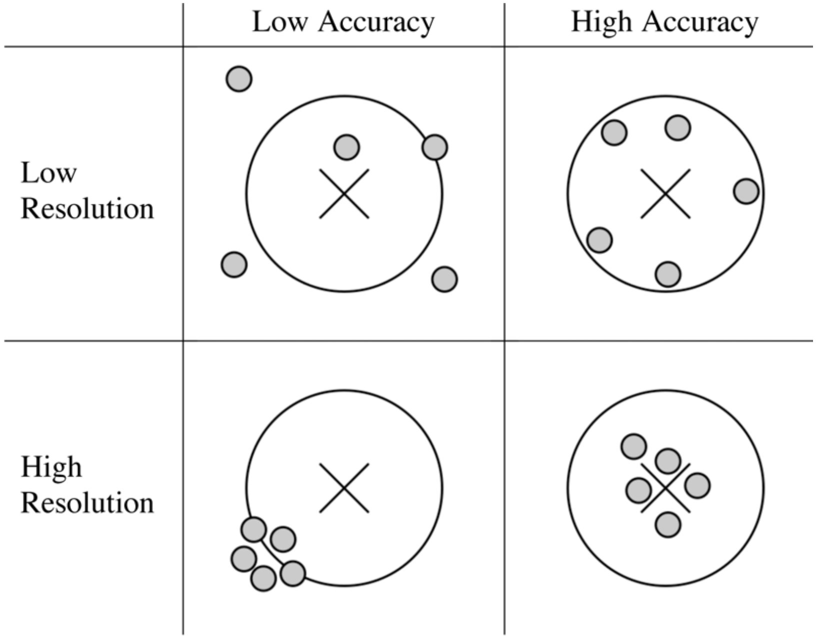
System Examples

- Communication technologies and system examples

- Radio Frequency (RF)
    - GPS
    - Galileo and Glonass
    - Mobile Phones
    - WLAN
    - UWB
    - RFID
- Infrared
    - Badge systems
- Optical
    - 3D tracking with stereo vision
    - (2D) barcodes
- Ultrasound
- Magnetic

Resolution vs. Accuracy

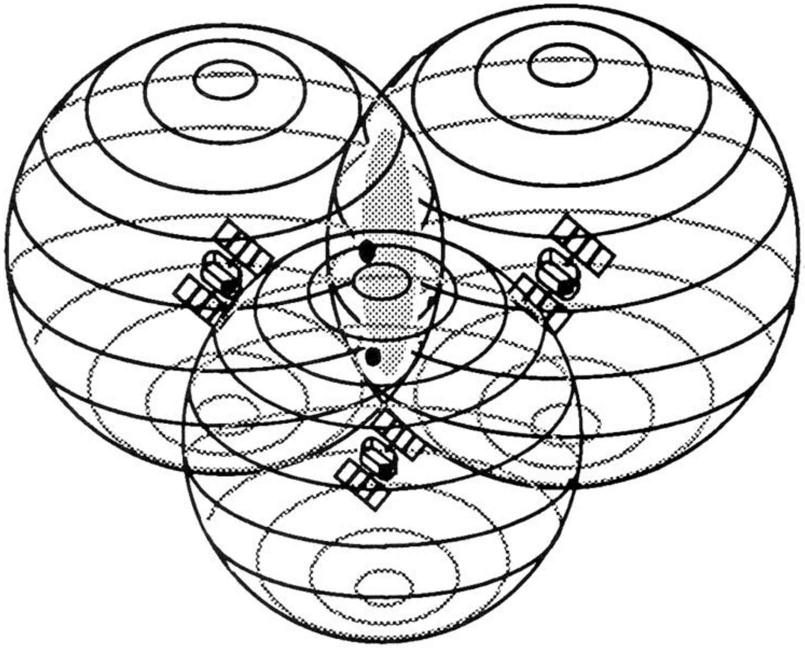
- Resolution (= precision) vs. Accuracy



- Example:
  - Which system is better?
    - IR system: resolution = room, accuracy = room
    - WLAN RSS system: resolution = 1cm, accuracy = 3m
  - WLAN? …
    If the application’s requirement is accuracy=room -> No!

GPS

- 24 satellites in 6 orbital planes with 4 satellites each
  - 32 satellites today (redundancy)
- Four measurements are required to determine latitude, longitude, height and receiver clock offset from GPS system time
- Three, if time or height is accurately known (almost never the case)
- Position update with less satellites possible (e.g., by Kalman Filtering)



GPS

- Provides accurate, continuous, worldwide 3D position and velocity information (and time)
- Principle
  - One-way time of arrival ranging: v=3x108m/s => t/s=3.33ns/m!
  - Unlimited number of users; they operate receive-only
- GPS system time
  - Global clock
  - Highly accurate atomic frequency standard onboard the satellites
  - Clock errors measured by Master Control Station (MCS) and forwarded to users
- Navigation data
  - Identification component: PRC (Pseudo Random Code), provides satellite recognition and status information
  - Position component: Location of satellite at time of signal transmission
  - Time component: Ranging code to determine satellite-to-user range

GPS: Accuracy

- GPS Error budget

GPS JPO PPS Pseudorange Error Budget

Segment Source	Error Source	GPS 1σ Error (m)
Space	Satellite clock stability	3.0
	Predictability of satellite perturbations	1.0
	Other (thermal radiation, etc.)	0.5
Control	Ephemeris prediction error	4.2
	Other (thruster performance, etc.)	0.9
User	Ionospheric delay	2.3
	Tropospheric delay	2.0
	Receiver noise and resolution	1.5
	Multipath	1.2
	Other (interchannel bias, etc.)	0.5
System UERE	Total (rss)	6.6

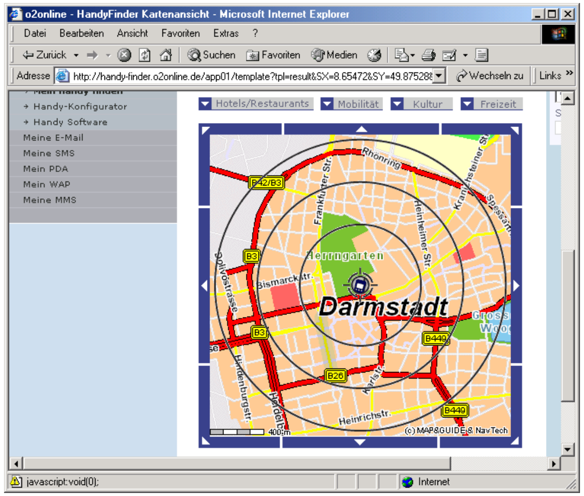
- Full accuracy since 1995, testing since 1978
- Selective Availability (SA) was an intentional degradation that induced an additional error of ~30m.
  Disabled on May 1, 2000 (Bill Clinton)

GPS: Augmentations

- Standard GPS issues
  - Line-of-sight required, does not work indoors
  - Accuracy of 6.6m not enough for all applications
- DGPS
  - Local Area DGPS
    - Accuracy improved by removing correlated (i.e., common) errors between two or more receivers performing range measurements to the same satellites
    - Stationary reference receiver broadcasts differential correction
    - Online and offline operation
  - Wide Area DGPS
    - INMARSAT: Accuracy 7.5m, hardly used
- AGPS
  - Reduce time of first fix. State of the art: 4 seconds
  - Use network resources (e.g., time, additional servers, etc.)
  - Receivers might not work without assistance (most mobile phones)

Mobile Phone Location

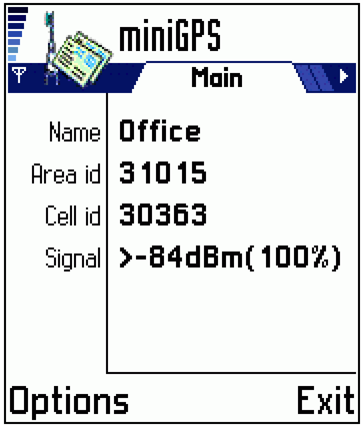
- Cell ID (network-based)
  - Network reports which cell you are using
  - Depends on base-station density
    - Good in urban environments, but also high density of „points of interests“
    - Maximum cell size: 35 km
  - Properties
    - Affords positioning of legacy handsets
    - Not always connected to nearest cell (load balancing)



O2 Handyfinder

Mobile Phone Location

- Cell ID (client-based)
  - Extract **Cell ID** from phone radio stack
  - In general, proprietary information needed for real geopositioning: mapping from Cell ID to longitude, latitude
  - Provider sends coordinates of base stations in **Cell Broadcast** messages
    - E.g.: Darmstadt, Mensa = CBS Code: 347547 552663 = WGS84: Longitude 8.6577°E, Latitude 49.8756°N
  - Properties
    - Handset is operating receive-only: unlimited number of clients, no additional costs
    - Additional software required on handset e.g. PSILoc miniGPS (has nothing to do with GPS)
    - State of the art in smartphones



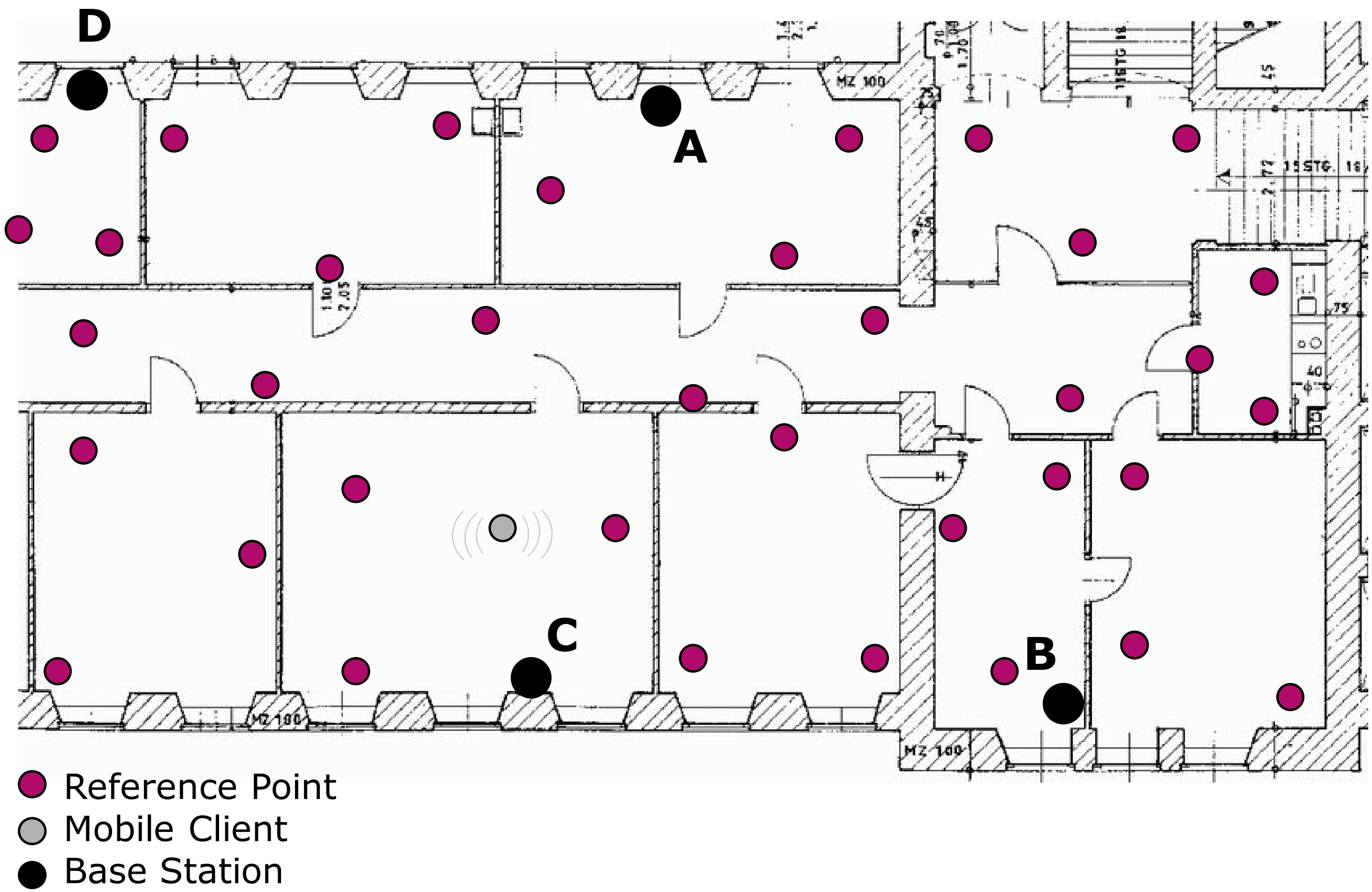
PSILoc miniGPS

WLAN

- SSID (=„Cell ID“)
  - Encode geographic location into SSID: No standard
  - Server provides mapping from the access point’s MAC address to geographic coordinates
  - PlaceLab
- Accurate Positioning
  - Requires at least 3 stations for Triangulation
  - Algorithms:
    - Nearest Neighbor
    - Multiple Nearest Neighbor
    - Neighbors Interpolation with RSSI-Map
- Accuracy:
  - 2-3 meters
  - RSSI depends on obstacles, dynamic factors like number of persons in a room

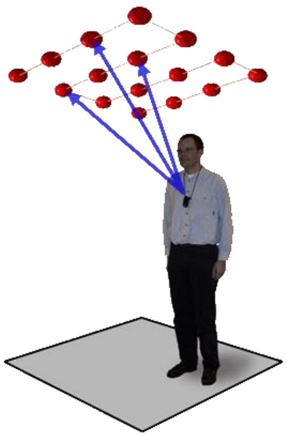
WLAN RSSI

- RSSI Map



Ultrasound

- Components
  - Badges (called „Bats“) with RF receiver and ultrasound transmitter
  - Ceiling-mounted ultrasound receiver grid
  - RF transmitters
- Infrastructure schedules ultrasound transmissions and requests Bats to send ultrasound pulses via RF link.
- Time measurement relatively easy: v=330m/s
- Accuracy: ~9cm, but only in absence of multipath and fading
- Systems: Active Bats, Cricket, Intersense products



(Passive) RFID

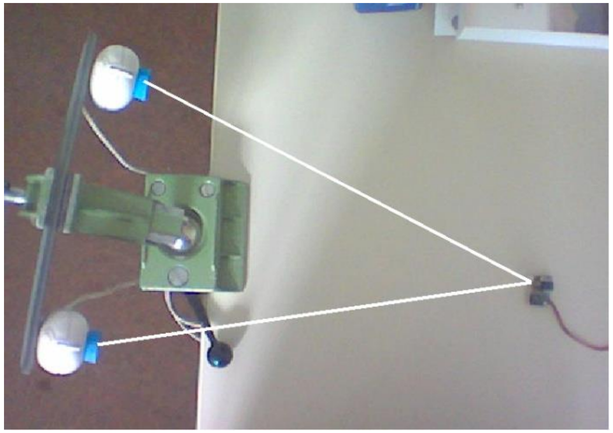
- RFIDs on landmarks
  - Idea: Put cheap RFID labels on street signs, shop windows, sidewalks, …
  - Readers in mobile devices
  - Energy problem:
    - Signal strength decreases with d^4
    - Power in mobile devices already critical -> short reading range

- RFIDs carried by users
  - Readers in infrastructure
    - Reading distances of 3-6m already possible
  - Issues:
    - Tracking without your knowledge possible
    - RFIDs can‘t be read out when worn close to the body

IR Optical Tracking

- Principle: Angle of Arrival (AOA)
- Systems
  - Optotrak
    - Accuracy: 0.1mm
    - Tracking rate: max. 4600 Hz / #tags
    - Number of tags: max. 512
    - Usually covers 3-4m^2 (operating table)
    - Expensive
  - ART
    - Designed for VR/AR applications
  - Mundo IRIS: Components
    - Active IR tags
    - USB or Firewire cameras
    - PC for Image Processing

Optotrak Certus

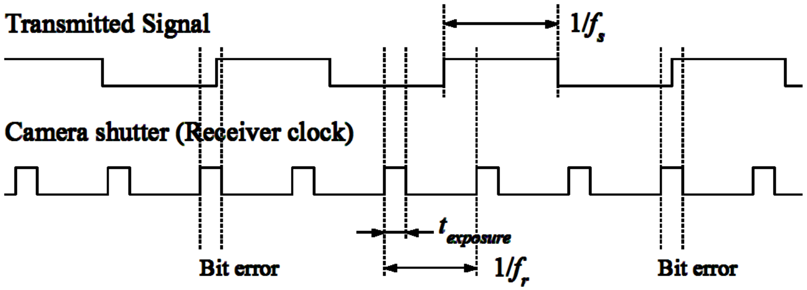


Mundo IRIS

Multiple users

- How to distinguish multiple tags?
- Rigid bodies: ART tree and glasses targets

- Modulate IDs on IR beam (implemented in Mundo IRIS)
  - Basic Idea:
    - Set sender‘s signaling slightly lower than frame rate
    - Use error correcting code to eliminate bit duplications
  - Tracking only possible during 1-bits
  - Receiver‘s sampling rate only 60 or even 30 fps -> ~0.5s for 8 bits



Sym.	Code
0	10
1	1110
S	111110

Location Models

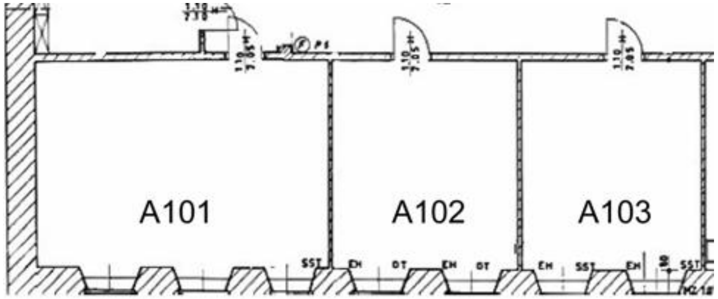
- A location model is a prerequisite for transforming raw sensor readings into a representation meaningful to applications

- Location Representation
  - Coordinates - e.g., World Geodetic System 84 (WGS84)
  - Symbolic location
- Model Functions
  - **Location function**: determine location of mobile/static users/objects
  - **Distance function**: provides a measure of the distance between two locations
- Model Relations
  - **Connected-to relation**: describes the interconnections between neighboring locations
  - **Contained-in relation**: topology is a mechanism for establishing spatial relationships between user and surroundings

Geometric Location Models

- Example: SQL with OpenGIS Geometry Model spatial extensions

```
CREATE TABLE room (name TEXT, poly POLYGON);
INSERT INTO room VALUES ('A101', GeomFromText
    ('POLYGON((0 0, 6 0, 6 4, 0 4, 0 0))'));
INSERT INTO room VALUES ('A102', GeomFromText
    ('POLYGON((6 0, 10 0, 10 4, 6 4, 6 0))'));
INSERT INTO room VALUES ('A103', GeomFromText
    ('POLYGON((10 0, 14 0, 14 4, 10 4, 10 0))'));
CREATE TABLE user (name TEXT, position POINT);
INSERT INTO user VALUES ('john', GeomFromText('POINT(7 3)'));
```



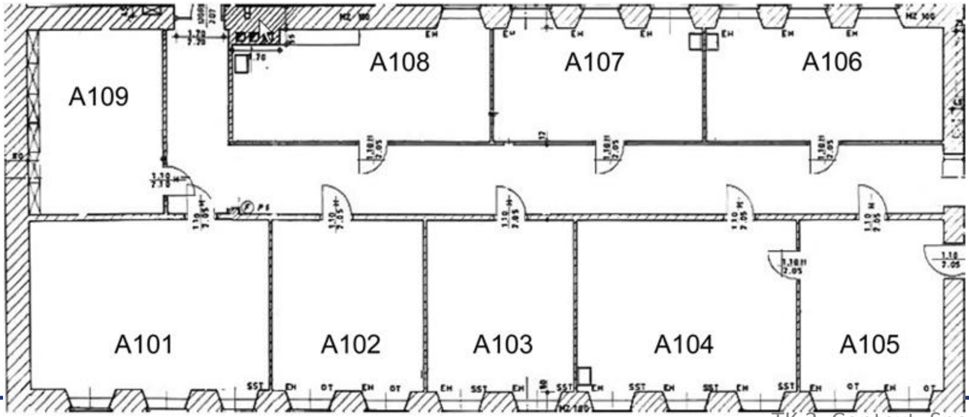
- **Location**: The location of a user can be determined by querying the user table.
  SELECT AsText(position) FROM user >> POINT(7 3)
- **Distance**: The shortest distance between the user's position and any point of the geometry of room A103 can be determined with the following query.
  SELECT Distance(poly, position) FROM room, user WHERE room.name='A103' >> 3.0
- **Connected-to**: The rooms next to A102 can be determined using the Touches function.
  SELECT b.name FROM room AS a, room AS b WHERE a.name='A102' AND Touches(a.poly, b.poly) >> A101, A103
- **Contained-in**: The following query determines the room names for users' locations.
  SELECT user.name, room.name FROM user, room WHERE Contains(poly, position) >> john, A102

Location Models

- Geometric Location Models
  - Contained-in relation can be derived from geometry
  - Connected-to relation has to be modeled explicitly
    - Problem with example before: “touches” does not mean that there is a connecting door
  - Shortest geometric distance does not necessarily reflect the distance a user would have to travel
- Symbolic Location Models
  - Set-based model
  - Hierarchical model
  - Graph-based model
  - Combined models

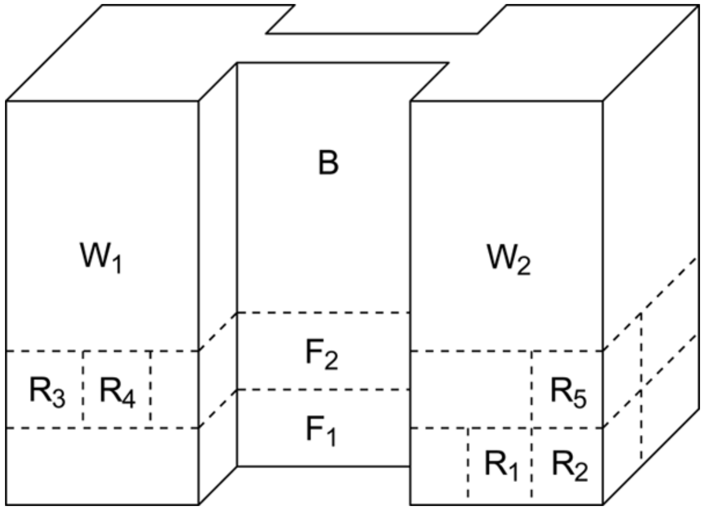
Set-based Model

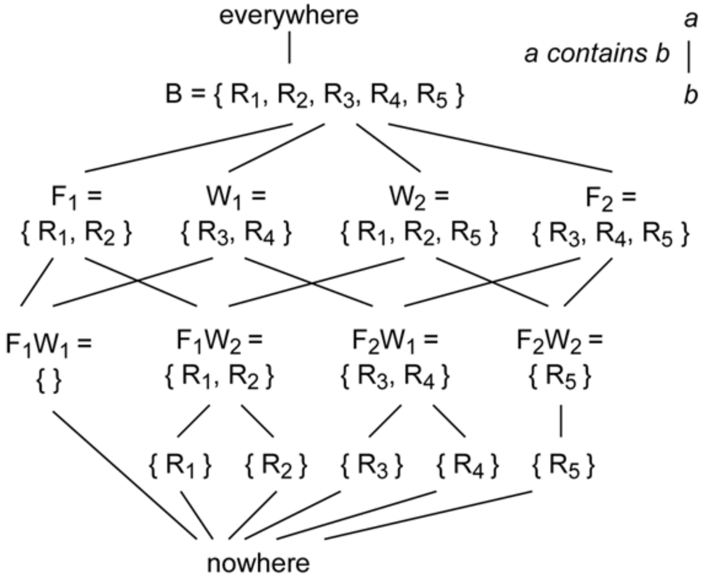
- Rooms sharing certain properties are grouped into sets
  - All rooms in floor 1, wing A: L_{A1} = {A101, A102, …, A109}
  - Neighboring locations: L_C = {A104, A105}
- Model allows to determine overlapping and containment
  - $L_1 \cap L_2 \neq \emptyset$ -> L_1 and L_2 overlap
  - $L_1 \cap L_2 = L_1$ -> L_1 fully contained in L_2
- Distances can be set into relation by comparing sizes of smallest neighbor sets, e.g., d(A105, A104) < d(A105, A101), because
  - The smallest set containing A105 and A104 is L_C,
  - The smallest set containing A105 and A101 is L_{A1}, and
  - $| L_C | < | L_{A1} |$



Hierarchical Model

- Locations are ordered according to containment relations
- Location l_1 is ancestor of location l_2 ($l_1 > l_2$), when l_2 is spatially contained in location l_1
    - If locations do not overlap -> containment tree
    - If locations overlap -> containment lattice (see below)
- Distances are compared by calculating the supremum (least upper bound) of a set of locations
- Model does not describe connections between locations; e.g., there could be stairs connecting R_2 and R_5 directly

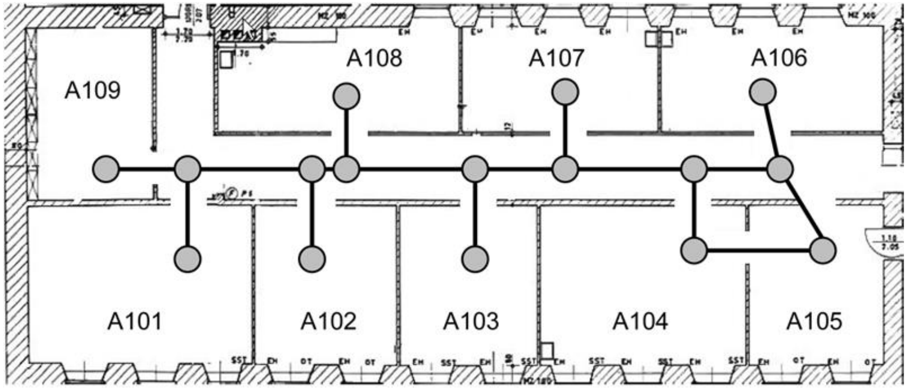




Graph-based Model

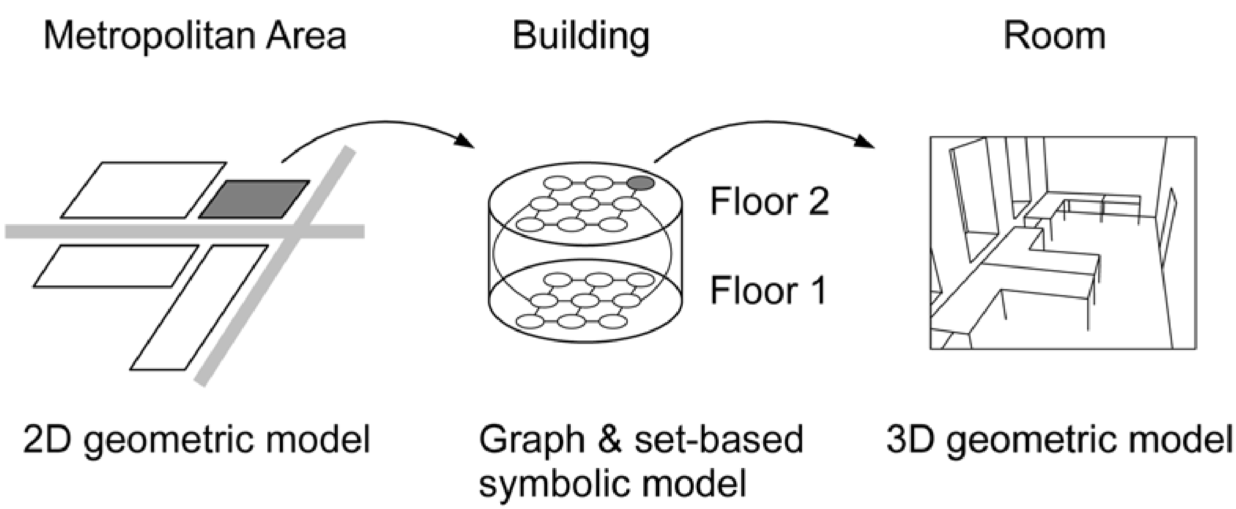
- Model is based on a graph $G = (V, E)$
  - Vertices V denote symbolic locations
  - Edges E denote connections between locations
- Edge directly represents the *connected-to* relation

  -> good for nearest-neighbor queries and navigation applications
- Distance between two locations is calculated as the minimum number of hops between the locations



Hybrid Model

- Hybrid models combine symbolic and geometric representations
- Example:
  - basis is a geometric model describing the extent of buildings using a global reference system, like WGS84
  - structure of buildings is then described by means of a symbolic model that combines the hierarchical and graph-based approaches
  - where needed, detailed geometric descriptions for rooms can be added as vertex attributes in the symbolic model



Summary: Location

- Location Systems
  - There is no silver bullet
  - System choice depends on application
    - Indoor/Outdoor: ambient light, required range
    - Energy consumption: unidirectional IR < RF < IR-Tracking
    - Resolution and Accuracy, Meaning of room boundaries
    - Number of clients: IR < IR-RF
    - Pure software solution … hardware
  - Properties: Resolution, accuracy

- Location Models
  - Location representation
  - Geometric location models
  - Symbolic location models