Location and Positioning Systems in Wireless LANs

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Summary

- Location Based Services (LBSs)
- Location classification
- Positioning base techniques
  - lateration, angulation, scene analysis, proximity
- Positioning systems
  - in ad-hoc networks
  - with additional hardware (GPS, IR, US...)
  - without additional hardware (Cell, 802.11, BT...)
- Positioning fusion

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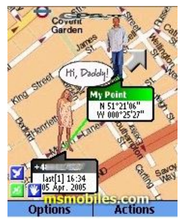
Why Positioning?

- Relevant LBSs:
  - E-911 Emergency assistance: Where are they?
  - Advertising: You are here!
  - Tracking: Where are you going?
  - Virtual Tour: I am close to...
  - Service discovery: What is here?
  - Network service: If they are there...



How positioning?

- Many LBSs ➔ many different requirements
  - E-911: on request (xy coordinates)
  - advertising + virtual tour: location changes (room, street)
  - network support: every X minutes (network area)
  - navigation: every X seconds (xy coordinates)
- Other requirements:
  - low power consumption, easy to use, pervasive devices...
  - user privacy

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Physical vs. Symbolic

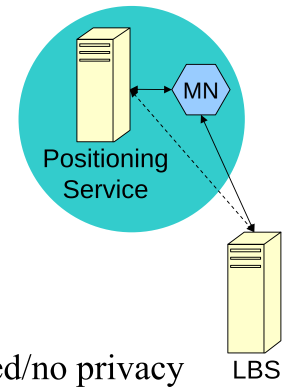
- Physical:
  - machine/computational related
  - WGM84 Location (GPS):
    - latitude, longitude, ellipsoid height (altitude)
- Symbolic:
  - human speaking/thinking related
  - Layered Location:
    - {Italy, Bologna, EngFaculty, DEIS, Lab2}

Absolute vs. Relative

- Absolute:
  - a unique reference system for every located object
  - either physical or symbolic
- Relative:
  - object location relative
  - typically physical
    - useful in an ad-hoc scenario

Centralized vs. Distributed

- Centralized:
  - one for all computes location
- Distributed:
  - each one computes its location



- Privacy issue:
  - network communication ➔ limited/no privacy
  - every disclosed location dependent information reduces user privacy

Accuracy & Precision

- Accuracy: error range (meters)
- Precision: error range confidence (percentage)
  - GPS: accuracy 10 meters, precision 95%
- Accuracy and Precision usually derived directly from the exploited positioning system and dependent on the current environment

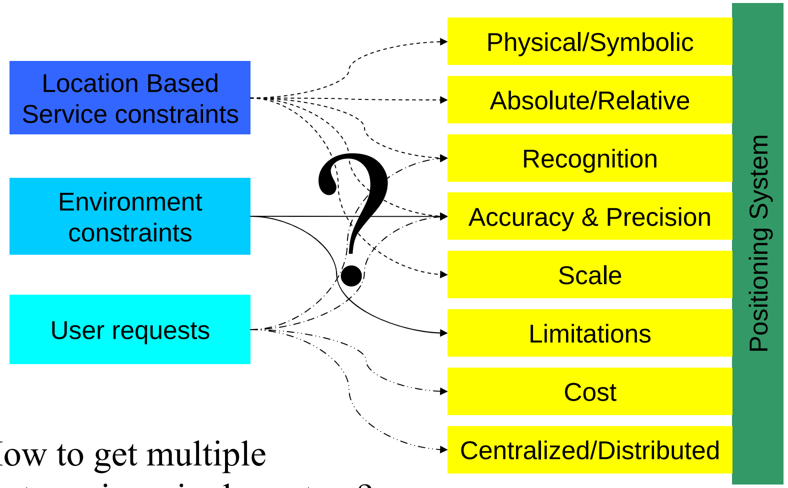
Scale, Recognition

- Scalability:
  - which area?
    - coverage area / infrastructure unit
  - how many users?
    - user / (infrastructure unit * time unit)
  - how much computation? middleware complexity?
- Recognition
  - Baggage tag#, Credit Card (!) vs. GPS

Cost, Limitations

- Cost
  - time, infrastructure, client
  - additional hardware, battery consumption
- Limitations
  - where/when?
  - indoor vs. outdoor

Project choices or technological constraints?



- How to get multiple features in a single system?

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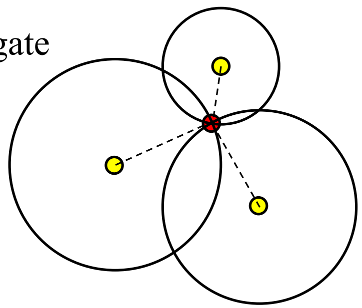
Lateration

- 2D ➔ 3 circumferences
  - more circumferences to mitigate distance measurement errors

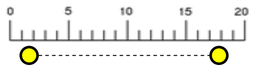


Reference point
Locating point

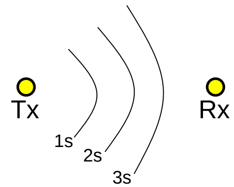
- note:
  - 2 variables, 3 measurements
  - 2 measurements only when locating point on the line between 2 reference points (circumferences are tangents)

Distance through...

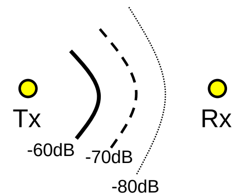
- Direct measurement



- Time of Arrival (ToA)
  - distance = signal speed * ToA



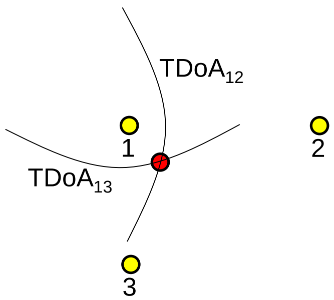
- Received Signal Strength Indication (RSSI)
  - Signal Attenuation $P_s(x) = \frac{P_t G_t G_r \lambda^\beta}{(4\pi x)^\beta}$

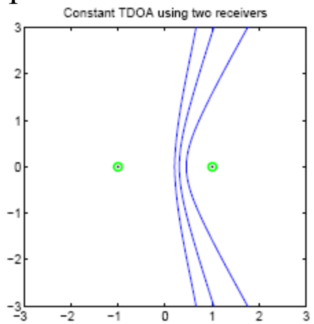


- Common technologies
  - InfraRed (IR), RadioFrequency (RF), UltraSound (US)

Time Difference of Arrival

- 2D ➔ 2(3) hyperboles
  - hyperbole: point set at the same Time Difference of Arrival from two reference points





three different TDoA:
0.4, 0.6 and 0.9 scale units

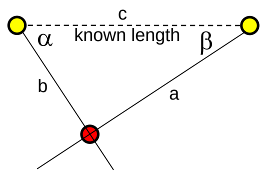
Angulation

- Prerequisites:
  - distance between reference points
- 2D ➔ 2 angles ➔ 2 measurements

Carnot's Theorem

$a^2=b^2+c^2-2bc\bullet\cos\alpha$
$b^2=a^2+c^2-2ac\bullet\cos\beta$

2 equations with
2 variables (a, b)

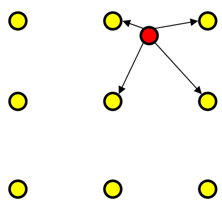


Eulero's Theorem

$$\frac{a}{\sin\alpha}=\frac{b}{\sin\beta}$$

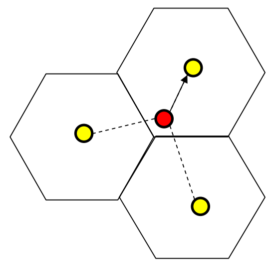
Scene Analysis

- Location inferred using passive observation of any physical phenomena (visual images, RSSI...) but without exploiting any physical value
  - i.e. without distances, angles, triangles, hyperboles...
- needs environment knowledge
  - environment must not change!
- Preliminary phase
  - environment observation and data collection
- Operational phase
  - environment observation and comparison between historical and observed data



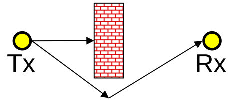
Proximity

- Current location ≡ nearest reference point
  - ToA, RSSI...
- Physical contact
  - mouse, keyboard, chairs
- Care of Cell
  - accuracy depends on cell range
- Automatic ID systems
  - credit card, electronic highway E-Toll systems (Telepass), fidelity card (fuel, marketplace...), access RFId (building entrance)

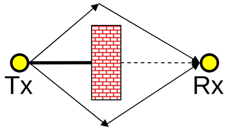


Sources of Error

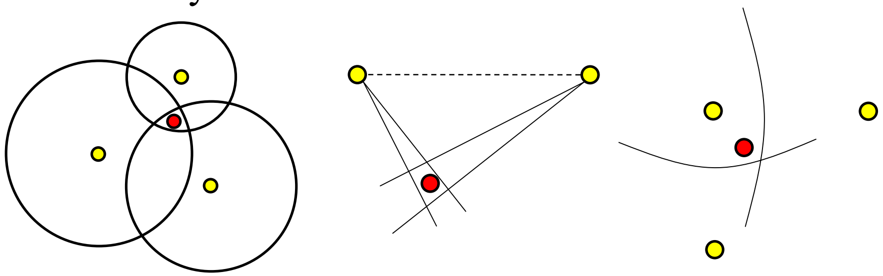
- Non Line Of Sight NLOS



- Fading:
  - Multipath
  - Shadowing



- Clock synchronization



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Ad-hoc networks

- Main Goal: obtain topology for
  - connectivity keeping
  - traffic optimization
- Cooperative Ranging Methodologies: every node plays the same role:
  1. receives ranging and location information from neighboring nodes
  2. solves a local positioning problem
  3. transmits the obtained results to neighbors
- Distributed algorithm with any global communication
  - useful only with little/no node movements

ABC

- Anchor node: node with apriori known location
- ABC: Assumption Based Coordinates
  - known information: relative distance between nodes
    - distances may be (are!) affected by errors
  - each anchor node create its own (relative) one-hop distance node map

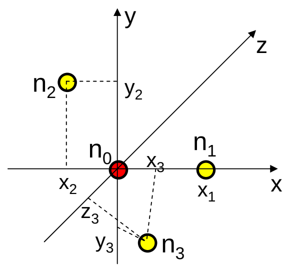
$$x_1 = r_{01}$$

$$\begin{cases} x_2 = \dfrac{r^2_{01} + r^2_{02} + r^2_{12}}{2r_{01}} \\ y_2 = \sqrt{r^2_{02} - x_2^2} \end{cases}$$

$$\begin{cases} x_3 = \dfrac{r^2_{01} + r^2_{03} + r^2_{13}}{2r_{01}} \\ y_3 = \dfrac{r^2_{03} - r^2_{23} + x_2^2 + y_2^2 - 2x_2x_3}{2r_{01}} \\ z_3 = \sqrt{r^2_{03} - x_3^2 - y_3^2} \end{cases}$$

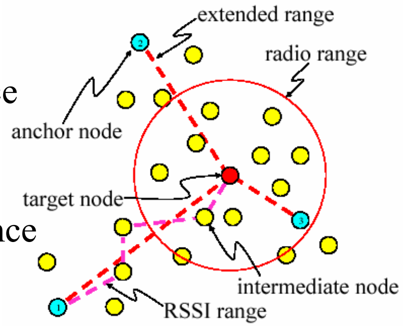
r_{jk}: distance between node j and node k

$n_1=(x_1, 0, 0)$
$n_2=(x_2, y_2, 0)$
$n3=(x_3, y_3, z_3)$



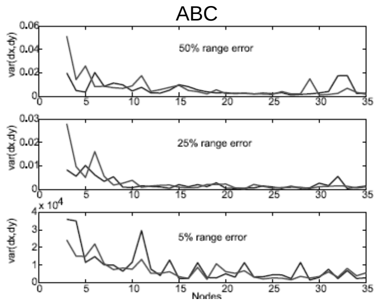
TERRAIN

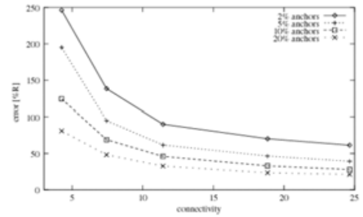
- hop-TERRAIN: Triangulation via Extended Range and Redundant Association of Intermediate Nodes
  - create a unique node map exploiting multi-hop distance node information
  - extended range = hop# * average node distance



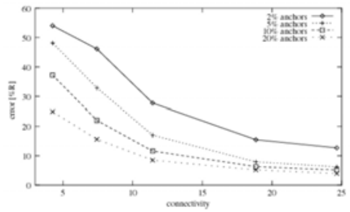
Refinement

- Refinement
  - use information only about visible nodes to reduce range estimation accuracy problems





hop-TERRAIN



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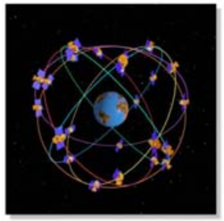
Additional hardware

- Special purpose hardware specifically developed and added to get location dependent information
  - RadioFrequency, InfraRed, (Ultra)Sound
- Special purpose hardware
  - improves accuracy and precision ☺
  - increases device size and power consumption ☹

Global Positioning System GPS

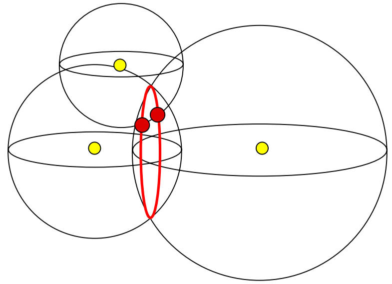
- USA Department of Defense (DOD)
- At least 24 operating satellites (now 29) orbiting at 11000 miles (ca. 18000km)
  - http://tycho.usno.navy.mil/gps.html
    - First satellite: 14 Feb 1989
    - Last satellite: 6 Nov 2004



- The most (only?) spread positioning system
- The LBS leveraging technology (maybe)

GPS: how does it work?

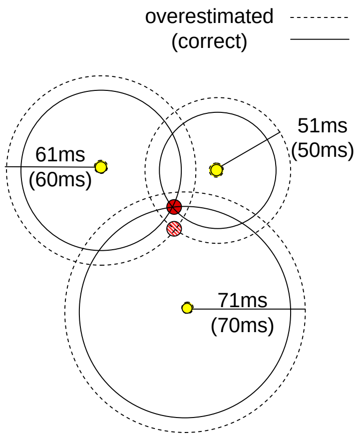
- What we know:
  - satellite position (almanac)
  - satellite-client signal time (ca. 0.06s)
    - distance=ToA*light speed
- How we use information:
  - Lateration + ToA



- 3 satellites ➔ 2 positions
  - 1 position with space/ultra-atmospheric elevation

GPS: synchronization

- ToA ➔ clock synchronization
  - satellite with atomic clock
    - great accuracy
  - client with quartz clock
    - worse accuracy
- 1 µs error → ca. 300m error
- Satellite-client clock synchronization with 4 (3 with 2D) satellites: client clock shifts until synchronization



2D synchronization example

GPS: Errors

- Several sources of error:
  - Atmospheric condition: ionosphere (0-30m) and troposphere (0-30m) refract GPS signal ➔ GPS signal speed changes
  - Ephemeris Errors: satellite orbital position (1-5m)
  - Clock drift: atomic clocks are not perfect (0-1.5m)
  - Measurement noise (0-10m)
  - Selective Availability: until 2000 introduced by DOD (0-70m)
  - Multipath: high buildings, mountains... (0-1m)

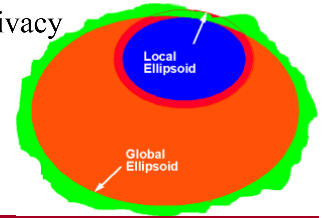
Differential GPS

- A base station which has precisely known position
- GPS Client performs standard computation
- Great accuracy (1-5m vs. 50-100m) comparing known location and satellite derived location

Source	GPS	D-GPS
Ionosphere	0-30m	Mostly Removed
Troposphere	0-30m	All Removed
Signal Noise	0-10m	All Removed
Ephemeris Data	1-5m	All Removed
Clock Drift	0-1.5m	All Removed
Multipath	0-1m	Not Removed
SA	0-70m	All Removed

GPS: Location

- Location:
  - physical + absolute
    - WGS84 World Geodetic System: latitude, longitude and ellipsoid height (continent motion aware)
    - Ellipsoid: a geometric, geodic, gravitational Earth model
  - distributed
  - cost: infrastructure vs. client
  - scale: completely distributed ➔ maximum scalability
  - no identification + distributed ➔ user privacy
  - accuracy: 100m/<1m, precision: 95%
  - limitations: only outdoor (need LOS)



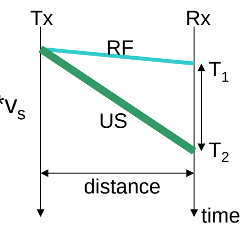
Active Badge

- Olivetti Research Laboratory (now AT&T Cambridge)
- InfraRed technology
  - A badge periodically emits a unique identifier
  - A sensor network collects badge signals
  - A central server collects sensor data
- Properties:
  - proximity
  - symbolic
  - absolute
  - identification
  - low cost
  - room accuracy
  - IR does not work properly with sunlight/fluorescence

Cricket

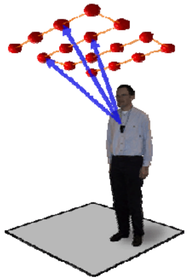
- MIT
- RadioFrequency (RF) / UltraSound (US) technology
- Fixed beacons periodically transmit RF signal with their position (fast signal) coupled with a US pulse (slower than RF)
  - lightening-thunder approach
- Properties:
  - ToA & Proximity
  - decentralized (user privacy)
  - accuracy 1.5m^2, precision ≈100%

distance=$(T_2-T_1)*v_s$



Active BAT

- AT&T
- UltraSound technology
  - a badge emits a unique identifier to a central server
  - central server:
    - triggers badge signal (via RF),
    - triggers ceiling-mounted receiver reset,
    - collect data,
    - computes badge position.
- Properties:
  - ToA, physical, absolute, identification, low cost, accuracy 9 cm, precision 95%



AHLoS: Ad-Hoc Localization System

- UCLA
- RF and US technology
- Lateration + ToA
  - RSSI vs. RF and US

Wins (900 MHz RF)

Medusa (US)

Property	RSSI	Ultrasound
Range	same as radio communication range	3 meters
Accuracy	2-4 m for WINS	2 cm for Medusa
Measurement Reliability	hard to predict, multipath and shadowing	multipath mostly predictable, time is a more robust metric
Hardware Requirements	RF signal strength must be available	US transducers and amplifier circuitry
Additional Power Requirements	none	tx and rx signal amplification
Challenges	large variances in RSSI readings, multipath, shadowing, fading effects	interference, obstacles, multipath

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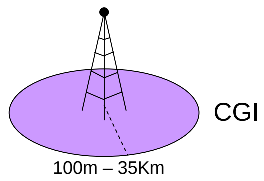
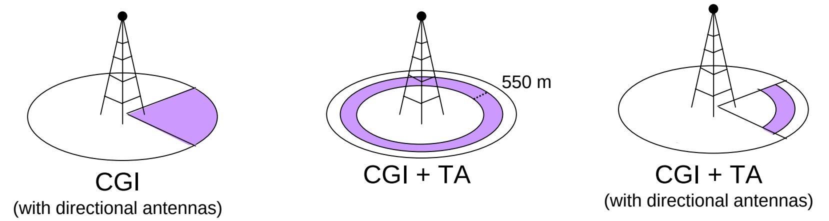
Without additional hardware: Exploit what you have

- Additional hardware:
  - device size
  - power consumption
  - you must have it
- Without additional hardware:
  - use what is already available for communication: GSM/GPRS/UMTS, Bluetooth, 802.11

Cellular Networks: GSM

- Network Based
  - Cell Global Identity (CGI)
  - Angle of Arrival (AoA)
  - Timing Advance (TA)
  - Signal Strength
  - Uplink Time of Arrival (UL-ToA)
  - Uplink Time Difference of Arrival (UL-TDoA)





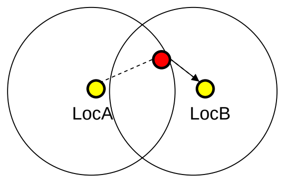
Cellular Networks: GSM

- Mobile Station based
  - Enhanced - Observed Time Difference (E-OTD ≡ TDoA)
    - at least three Base Transceiver Station
  - Timing Advance
    - at least 2 forced handovers

Technology	Computation locality	User Controlled Privacy	Modifications		System Accuracy	
			HW	SW	urban environment	rural environment
CGI	network	no	none	none	> 100m	< 35 Km
CGI+TA	network	no	none	none	> 100 m	circle of arc of 550 m
UL-ToA	network	no	GPS for clock synch		150 m	50 m
UL-TDoA	network	no	GPS for clock synch		50 m	80 m
E-OTD	MS	yes	none	yes	200 m	60 m

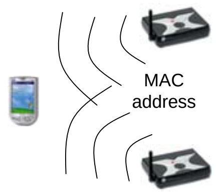
Bluetooth

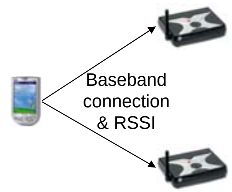
- Bluetooth is low cost and short range ➔
  - proximity, accuracy < BT range (ca. 10m)
  - symbolic, absolute, distributed
- Proposed solution:
  - BT devices installed in Point Of Interests (POIs)
  - location DB: BT POI MAC Address ➔ POI Location
  - multiple visible BT devices:
    - select the closest one ➔ strongest RSSI



Sequence Diagram

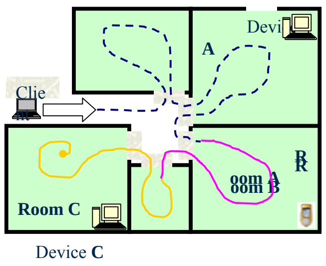
1. POIs broadcast MAC address
2. Device listen to POIs
3. Device connects to visible POIs
4. Device requests connection RSSI
5. Device computes its location
   - compares RSSI
   - avoid bouncing effect

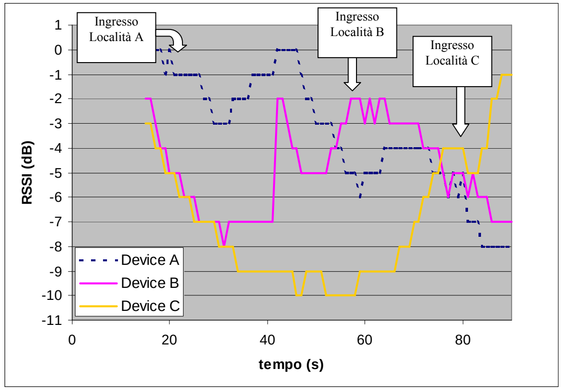




Example

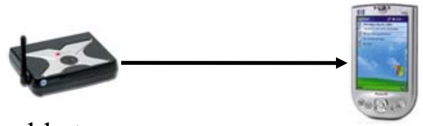
- easy to develop
- easy to deploy
- really cheap
  - BT device < 25 €





Bluetooth: privacy levels

- I want to know which POIs are close to me, but Do I really want POIs know I am close to them?
- BT client:
  - inquiry on
    - every BT POI close to me is able to see me
  - page scan on (connect), inquiry off
    - BT POIs are not able to see me, but could try to connect to me if they know my address (like a blind connect)
  - inquiry off, scan off
    - stealth mode: none see me
      - if I do not connect to other devices



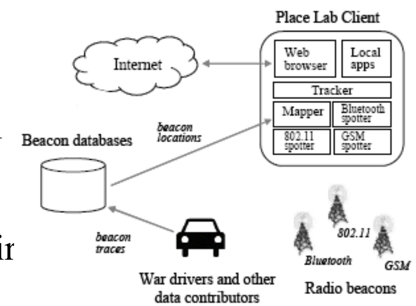
Bluetooth: privacy levels

- Three privacy level:
  - low: inquiry on, page on
    - BT client is discoverable
  - medium: inquiry off, page on
    - BT client is discoverable only if POIs know its address
    - BT client discloses its location when connects to BT POIs
  - high: inquiry off, page off
    - BT client is not discoverable
    - BT client does not connect to POIs
    - RSSI not available ➔ multiple possible POIs

PlaceLab

- Binds visible 802.11 AP MAC address to location information

1. users cooperatively create an AP-Location DB
2. users download DB
3. users exploit DB to infer their location



more than 2.2 million radio beacons, primarily 802.11 access points

- PlaceLab client performs positioning autonomously ➔ user privacy

PlaceLab features

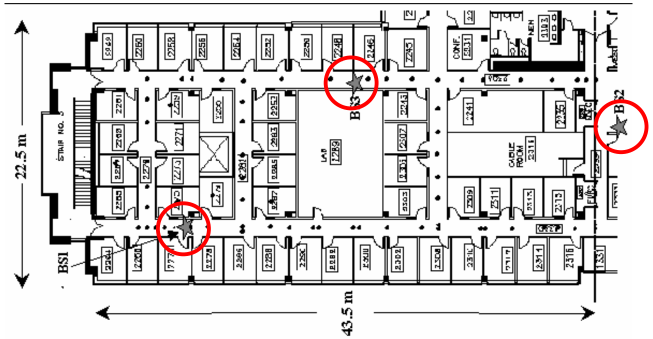
- Multiple devices to improve
  - accuracy, precision, covered area, provisioning time

Test Subject	GPS		GSM		802.11	
	coverage	avg. gap	coverage	avg. gap	coverage	avg. gap
Immunologist	12.8%	68 min	100.0%	-	87.7%	1.6 min
Home maker	0.6%	78 min	98.7%	2 min	95.8%	1 min
Retail clerk	0%	171 min	100.0%	-	100.0%	.
Average	4.5%	105 min	99.6%	1 min	94.5%	1.3 min

Test Environment	802.11		GSM		802.11 + GSM	
	accuracy	coverage	accuracy	coverage	accuracy	coverage
Urban	20.5 m	100.0%	107.2 m	100.0%	21.8 m	100.0%
Residential	13.5 m	90.6%	161.4 m	100.0%	13.4 m	100.0%
Suburban	22.6 m	42.0%	216.2 m	99.7%	31.3 m	100.0%

RADAR: concepts

- Scenario: 802.11 WLAN
- Scene analysis through RSSI
  - 2 steps: off-line phase, real-time phase



RADAR: off-line phase

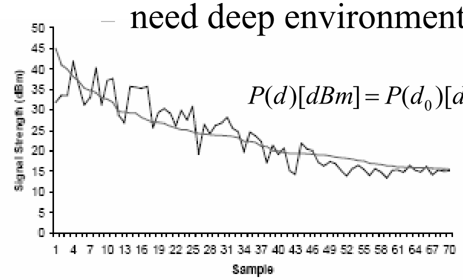
- off-line phase: empirical data collection
  - mobile client/APs clock synchronization
  - mobile client periodically **broadcasts UDP** packets while **user records its location** and orientation
  - **APs collects** and records UDP packet (mean) **RSSIs** with corresponding timestamp
  - a server merges data collected from every AP
- RSSI collection at the infrastructure side

RADAR: real-time phase

- real-time phase: device tracking
  - mobile client periodically broadcasts UDP packets
  - a centralized server computes user location
    - nearest neighbor neighbors in signal space (NNSS) with Euclidean distance among RSSI samples
    - NNSS-AVG
    - History Based Algorithm
- To improve accuracy/precision:
  - multiple nearest neighbors
  - multiple samples (positioning, not tracking)
  - more data collection

RADAR: alternative off-line phase

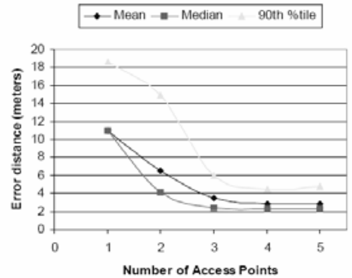
- off-line phase: radio propagation model
  - no more data collection
  - Wall Attenuation Factor (WAF) model to calculate hypothetic RSSI
  - need deep environment knowledge

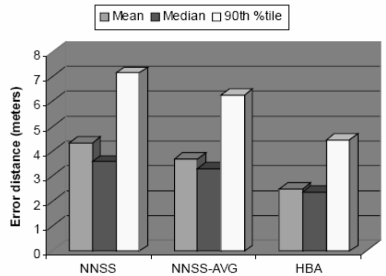


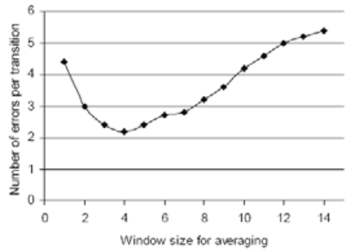
$$P(d)[dBm] = P(d_0)[dBm] - 10n\log\left(\frac{d}{d_0}\right) - \begin{cases} nW*WAF & nW<C \\ C*WAF & nW\ge C \end{cases}$$

RADAR: features

- physical
- absolute
- centralized
- low cost?
  - data collection is time consuming





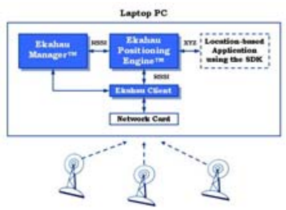


Ekahau: concepts

- "World is taken to be **stochastic**, **not deterministic** and one accepts the fact that the measured **signals are inherently noisy**"
- Model calibration:
  - a machine learning problem: environment implicitly modeled through **scene analysis** (RSSI)
- Rail tracking:
  - current location probably **close to recent location**
  - users follows **legal paths** (e.g. does not walk through wall) ➔ Hidden Markov Model

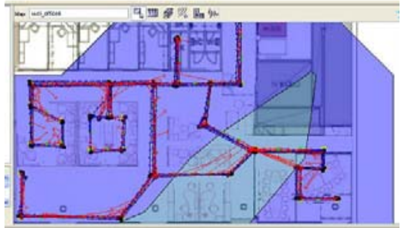
Ekahau: architecture/principles

- Similar to RADAR but...
  - **mobile device collects RSSI** data and sends it to a centralized server which computes device location
  - mobile device is able to choice when/if server performs positioning ➔ more **privacy**
  - **Rail tracking**



Ekahau: features

- **physical & symbolic**
- absolute
- low cost?
  - data collection is time consuming
- privacy: do we really trust Ekahau server?

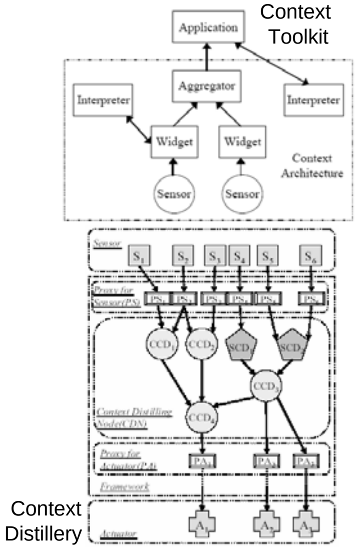


Summary

- Location Based Services (LBSs)
- Location classification
- Positioning base techniques
  - lateration, angulation, scene analysis, proximity
- Positioning systems
  - in ad-hoc networks
  - with additional hardware (GPS, IR, US...)
  - without additional hardware (Cell, 802.11, BT...)
- **Positioning fusion**

Sensor Fusion

- N data sources aggregated to provide M information output
- raw data → Sensor Fusion → structured data
- How aggregate raw data?
- Which data visible form the app?
- Which information to provide?

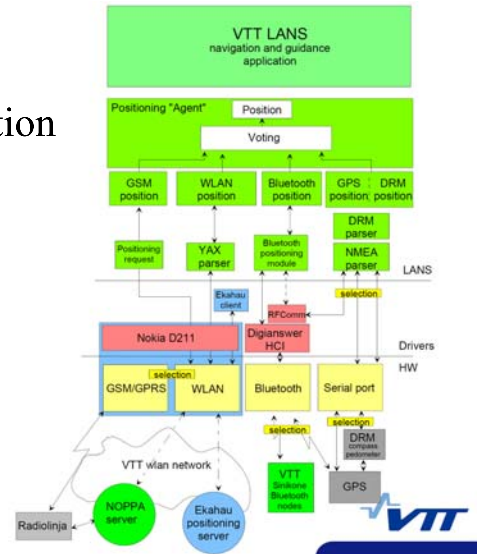


Positioning Fusion

- no data aggregation, just information selection
- Voting mechanism:

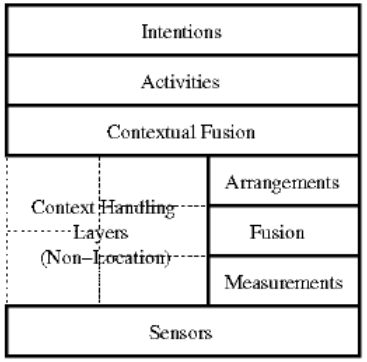
$$k_n = \frac{1}{t_{age} * v + \varepsilon}$$

  - v is velocity constant [m/s]
  - t_{age} is age of the fix [s]
  - ε is error estimate [m]
- Select $\max(k_n)$

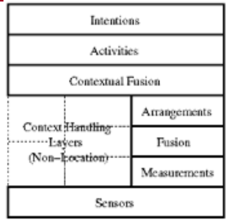


Location Stack (1/4)

- OSI-like abstraction layering
- Design principles:
  1. there are fundamental measurement types
  2. there are standard ways to combine measurements
  3. there are standard object relationship queries
  4. uncertainty must be preserved
  5. applications usually concerned with activities

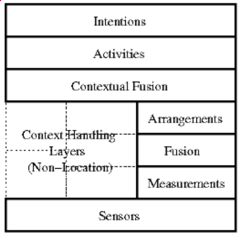


Location Stack (2/4)



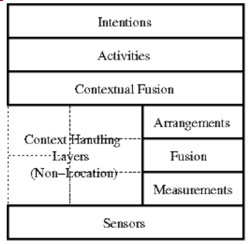
- Sensors
  - contains: hw/sw sensors
  - exports: **raw data** in variety of formats
- Measurements
  - contains: algorithms from raw data to canonical measurements types
  - exports: **canonical measurement** values
- Fusion
  - contains: measurement fusion through probabilistic mechanisms; capabilities, redundancies, and contradictions are exploited to reduce uncertainty
  - exports: **query** or **event interface** to provide location information

Location Stack (3/4)



- Arrangements:
  - contains: probabilistically reasoning about relationships (e.g. proximity, containment, geometric formations) between objects; convert location information between absolute and relative coordinates
  - exports: query or event interface to **relationships between objects**
- Contextual Fusion
  - contains: merging location data with other non-location contextual information
  - exports: an interface allowing applications to **recognize interesting states**, sequences, or situations

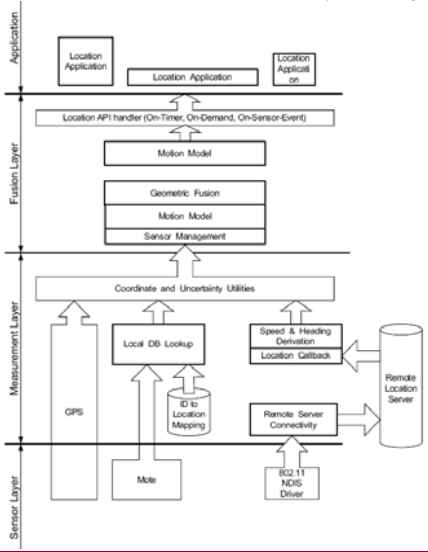
Location Stack (4/4)



- Activities
  - contains: a system (e.g. a learning machine), for categorizing all available context information into activities. Activities are semantic states, i.e. an application's interpretation of the state
  - exports: **an application specific interface**
- Intentions
  - contains: the cognitive desires of users

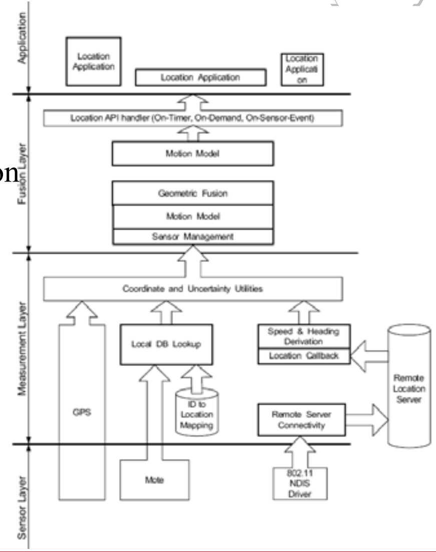
Universal Location Framework (1/3)

- Sensors
  - GPS, 802.11, Mote (a Berkeley sensor)
- Measurements: WGS-84
  - GPS: raw data
    - uncertainties added
  - 802.11: RADAR like
    - altitude added
    - 802.11 battery consumption
  - Mote: proximity → WGS-84
    - forcing from symbolic to physical location



Universal Location Framework (2/3)

- Fusion
  - Sensor Management
    - exploited sensor → location information accuracy/precision
  - Motion Model
    - speed and orientation
  - Fusion Stage
    - Bayesian filter
- Location API
  - automatic, manual, periodic



Universal Location Framework (3/3)

- OSI
  - protocol stack
    - →bottom-up/top-down
- Location Stack
  - middleware components
    - →bottom-up only

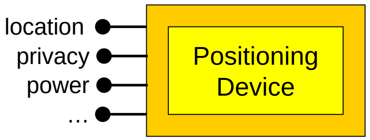
- How to provide raw data to upper layers?
- How to control sensors from upper layers
  - e.g. turn on/off devices

Our Proposal: principles

- Opaque approach (vs. transparent one):
  - Smart apps are able to easily interact with devices
  - Standard Apps requests are middleware-mediated
    - both data and management
- Cross layering architecture (vs. stack one)
  - privacy
  - power saving
  - uncertainty control/analysis
  - physical vs. symbolic → positioning system selection

Device Abstraction

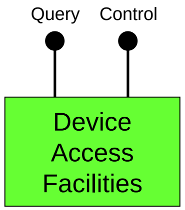
- Device Capabilities: Which are device features?
  - location information
    - physical vs. symbolic
    - accuracy & precision
  - privacy levels
    - high / medium / low
  - power consumption
    - high / medium / low
  - …
- Device Control: Which features am I able to change?
  - turn device on/off
  - change privacy level
  - power consumption selection
  - …



Altering a feature may affect other features:
e.g. BT: high privacy ➔ low accuracy / precision

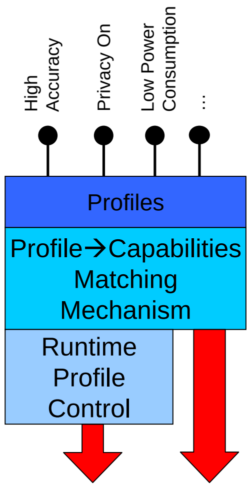
Device Access Facilities

- Smart apps may access to device directly…
- Query/Control methods to interact with devices aggregately
  - Query
    - how many devices are able to…?
    - provide every device which…
  - Control
    - turn on/off every device which…



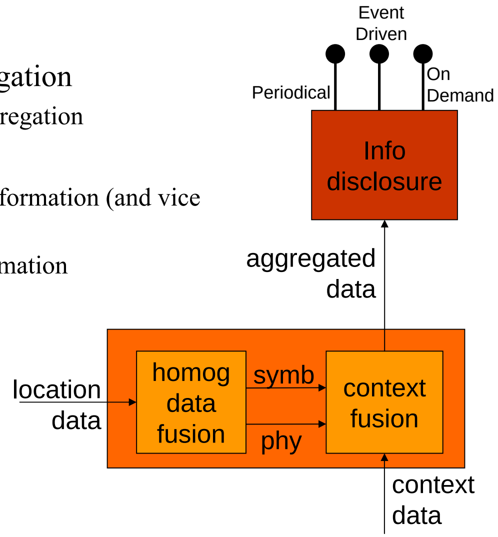
Profiling

- …but apps must be not too much smart.
- Profile selection
  - Profile: a set of device capabilities
    - Low Power Consumption: turn off every device without “Low Power Consumption” capability
    - Privacy On: turn off every device without “High Privacy” capability
    - High Accuracy/Precision…
  - Check for profile collision
    - e.g. High Accuracy vs. Low Consumption
- Profile observation
  - on request: when apps select a profile
  - at run time: checking for profile maintenance (e.g. accuracy is time varying)



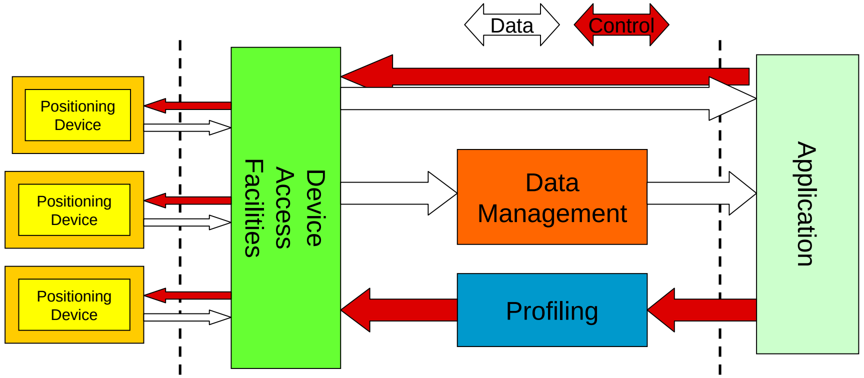
Data management

- Data Fusion
  - homogeneous data aggregation
    - e.g. symbolic location aggregation
  - context data aggregation
    - physical to symbolic transformation (and vice versa)
    - other context related information
- Information disclosure
  - on demand
  - event-driven
  - periodical



Overall Architecture

- Middleware:
  - supplies useful facilities to easily interact with devices
  - interacts with devices to guarantee profile observation
  - aggregates data to provide more sophisticated information



Conclusions and On going work

- Try to provide easy to use **high level API**
  - but let apps to interact with devices directly
- Provide a easy to use **query/control interface**
- Try to **aggregate** similar positioning devices
  - but without hiding their **peculiarities**
- Provide multiple system **behaviors**
  - with well defined differentiations
- Provide to apps as many as possible **information about devices**
  - but only if explicitly requested

Any question?

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