Indoor Positioning Technologies and Systems

From Theory to Practice

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Outline

Introduction

Outdoor Positioning

Indoor Positioning

Airplace Platform

Conclusion

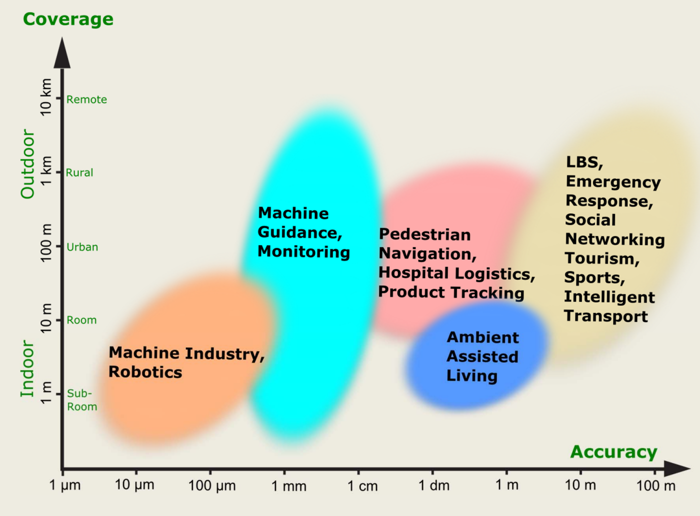
Motivation for Positioning

- Target tracking
- UAV missions
- Missile flight

- Network: 100m (cep67), 300m (cep95)
- Mobile: 50m (cep67), 150m (cep95)

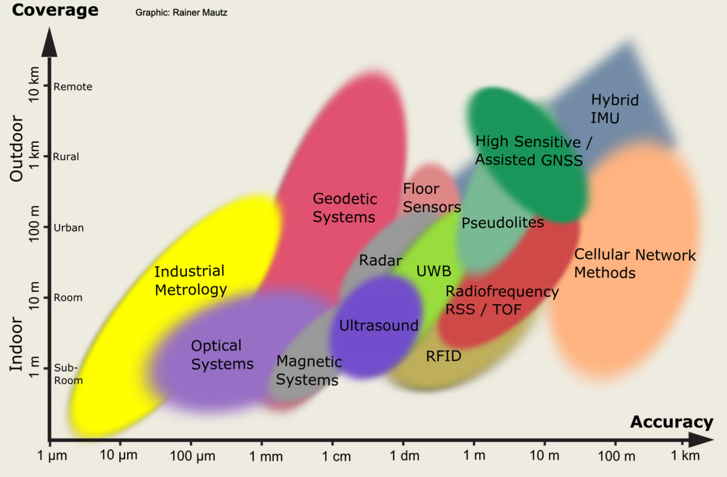
- Navigation
- Guidance
- POI locator

Applications of Positioning Systems



Rainer Mautz, 2011

Technologies for Positioning



Rainer Mautz, 2011

Satellite-based positioning

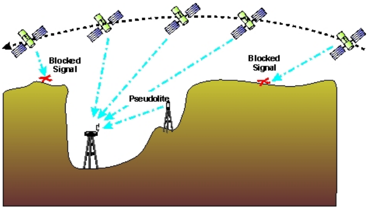
source: nist.gov

source: NASA

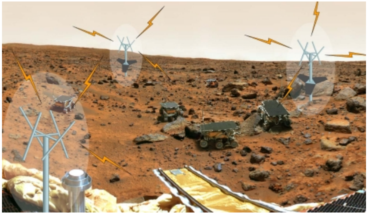
Facts

- GPS started in 1973 and became fully operational in 1994 (originally 6 constellations with 4 satellites, 31 as of 2008)
- Position determined by precisely timing the satellite signals (4 satellites required for 3D position, 3-5m accuracy)
- Russian GLONASS, European Galileo (planned 2014), Chinese COMPASS (planned 2020), India and Japan follow

Pseudolites



Source: wirelessdictionary.com



Self-Calibrating Pseudolite Array, Stanford ARL

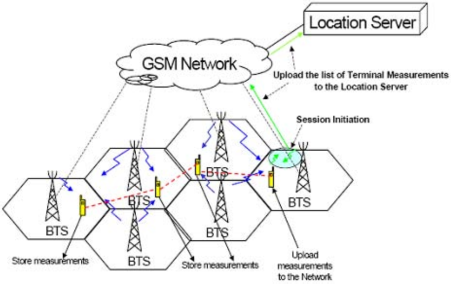
Objective

Augment satellite coverage in severely shadowed environments (e.g. mining pits, planetary rover navigation, urban canyons)

Features

- Requires ground-based transceivers and achieves submeter level accuracy
- Synchronization, multipath, near-far problem and legal issues

Cellular Networks (GSM, UMTS, ...)



Source: FP6 IST-MOTIVE project

Source: wikipedia

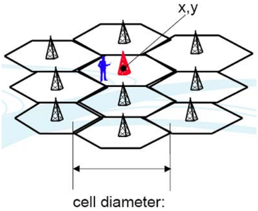
Objective

- GPS is battery hungry, has high start-up time, low availability in urban areas
- Use signalling in cellular networks for positioning, as a GPS back-up solution or to enhance GPS (A-GPS)

Cell IDentity (CID)

Measurements

Unique cell identifier

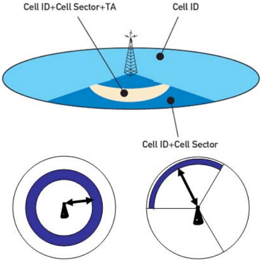


Advantages

- Low Cost: No modifications to handset or network
- Usable with existing equipment
- Fast response: No calculations needed

Disadvantages

- Low accuracy ranging from 50m (urban) to 30km (rural)
- Serving cell is not always the nearest cell



Angle of Arrival (AOA)

Measurements

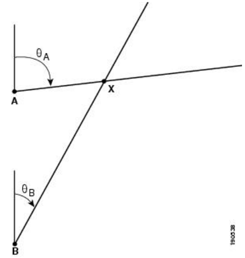
Signal arrival angle

Advantages

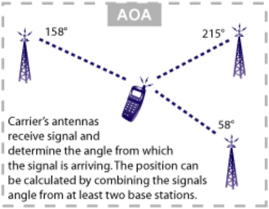
- Requires only 2 base stations
- No modifications to the mobile devices

Disadvantages

- LOS conditions
- Low accuracy
- Additional equipment (antenna arrays, directional antennas)



Source: cisco.com



Source: e-cartouche.ch

Time of Arrival (TOA)

Measurements

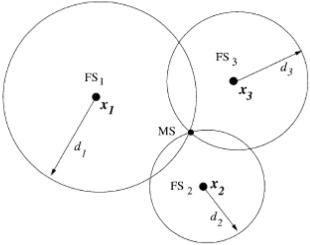
Signal propagation time between the transmitter and the receiver

Advantages

- No modifications to the devices

Disadvantages

- Knowledge of the exact transmission times
- Precisely synchronized clocks (e.g. 100 nanoseconds can result in 30 meters distance error)
- Requires additional equipment (Measuring Units)



Source: Stuber G.L., 1999

$$\tau_i = \frac{d_i}{c}$$

Time Difference of Arrival (TDOA)

Measurements

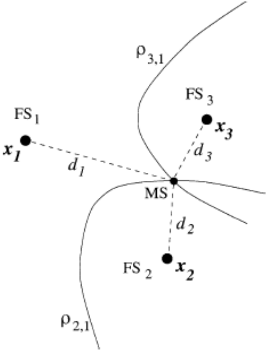
Time differences of the signal arriving at multiple base stations

Advantages

- Exact time of signal transmission is not required
- Good accuracy, 60m (rural) 200m (urban)

Disadvantages

- Requires additional equipment (Measuring Units) at the base stations
- Synchronization is still required



Stuber G.L., 1999

$$\rho_{i,j} = \frac{d_i - d_j}{c}$$

Received Signal Strength (RSS)

Measurements

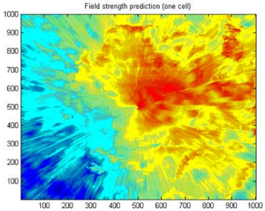
Signal strength of the transmitted signal

Advantages

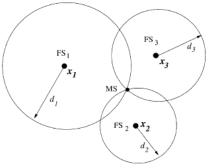
- Already monitored as part of the standard network functionality
- No modifications to the devices
- Low deployment cost

Disadvantages

- Moderate accuracy in rural and urban areas
- Requires calibration of the signal propagation model



Source: Alcatel, 2002



Source: Stuber G.L., 1999

$$rss_i[dBm] = K - 10n \log d_i$$

RSS Cellular Positioning Video

Why Indoor Positioning?

- People spend most of their time indoors, e.g. shopping malls, airports, university campuses

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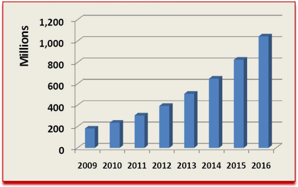
- Massive availability of mobile devices with wireless connectivity

Global Smartphone Sales, 2009-2016



Source: Telecom Trends International, Inc.

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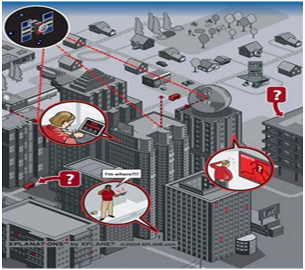
- Massive availability of mobile devices with wireless connectivity
- Satellite-based geolocation, e.g. GPS, is infeasible indoors



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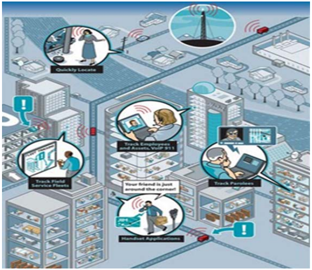
- Indoor location-aware applications, e.g. in-building guidance, asset tracking, event detection

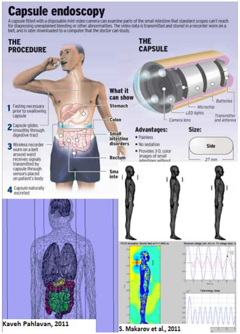


Target Indoor Environments

Source: google images

Inside the Human Body

Inside the Human Body



Capsule Endoscopy

Positioning of medicine capsules inside the human body using RF signals (K. Pahlavan, CWINS Group)

Center for Intelligent Systems & Networks

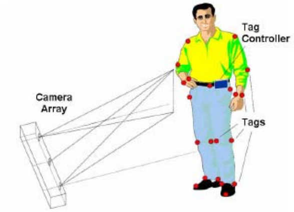
Infrared (IR)

Measurements

Custom IR cameras

Advantages

- Firefly delivers 3mm accuracy
- Tags are small and light-weight
- Simple system architecture, low installation and maintenance cost



Firefly by Cybernet System Corporation

Disadvantages

- Interference from florescent light and sunlight
- Expensive hardware (e.g. Firefly: 1 camera array + 1 tag controller + 32 tags = $27500, 2009)

AT&T Labs Cambridge

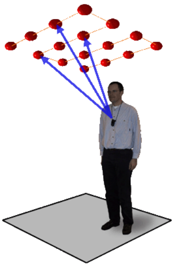
Ultrasound

Measurements

TOA, TDOA

Advantages

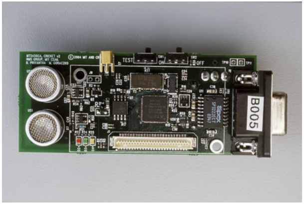
- Inexpensive and easy to install
- Centimeter level accuracy



Active Bat by AT&T Labs Cambridge

Disadvantages

- Temperature dependency, affected by noise sources (e.g. jangling metal objects)
- Suffer from reflected ultrasound signals (multipath, Doppler shift)



Cricket system, MIT

Ultra Wide Band (UWB)

Measurements

AOA, TOA, TDOA, signal reflection

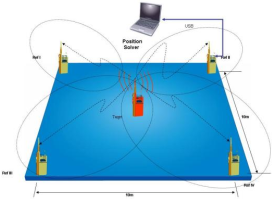
Advantages

- No LOS requirement, no multipath distortion, less interference, high penetration
- Easily wearable and light tags
- Very accurate (e.g. Ubisense has 15cm accuracy in 3D)

Ubisense system

Disadvantages

- Short range and computational cost
- Expensive equipment (Ubisense costs ~$17000, 2009)



Mitsubishi Electric Research Labs

Radio Frequency IDentification (RFID)

Measurements

Cell of Origin, Signal Strength

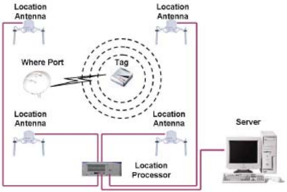
Advantages

- Penetration, unobtrusive installation
- Low power system, light and easy to carry tags

Disadvantages

- Numerous components installed and maintained
- Short range, close proximity

RFID system by RF Code



Wherenet Real Time Locating System

Magnetic

Measurements

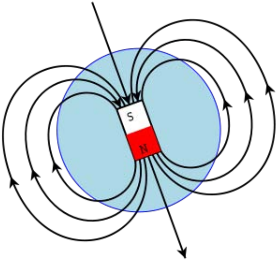
Magnetic flux density (coil or permanent magnets)

Advantages

- Centimeter level accuracy
- Magnetic sensors are small, robust and cheap
- Penetration through buildings

Disadvantages

- Complexity of magnetic field and disturbances
- Limited coverage range



Source: wikipedia

MotionStar Wireless System

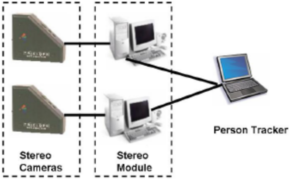
Optical Systems

Measurements

images, video

Advantages

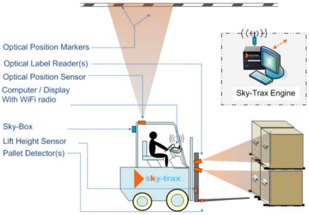
- High accuracy
- No user carried equipment



Easy Living system by Microsoft

Disadvantages

- Invasive installation, difficult to scale, high processing power
- Unreliable in dynamic environments (LOS required, light conditions, bad weather, fires)



sky-trax system

Inertial Measurement Units (IMU)

Measurements

3D acceleration, 3D gyroscope, digital compass, dead reckoning

VTT Research Center, Finland

Advantages

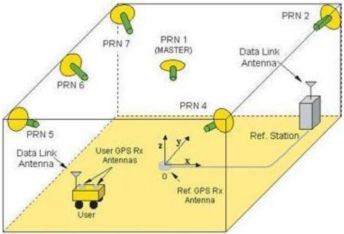
- No infrastructure is required, sensor integrated into smartphones
- Light-weight, low power

Disadvantages

- Relative positioning system: requires initial location and frequent updates
- Drift introduces error

Source: insidegnss.com

Why WiFi?



Source: gpsworld.com

- Installation of dedicated equipment vs Ubiquitous deployment of WiFi infrastructure (APs)

Why WiFi?

Source: cisco.com

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Why WiFi?

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- Specialized hand-held devices vs WiFi-enabled smartphones and tablets

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Source: gottabemobile.com

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Why RSS measurements?

Source: crfs.com

- AOA/TOA/TDOA measurements require additional hardware at the base stations or the mobile device

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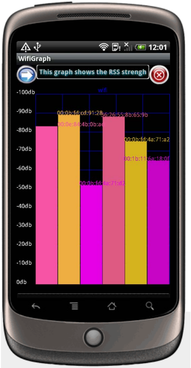
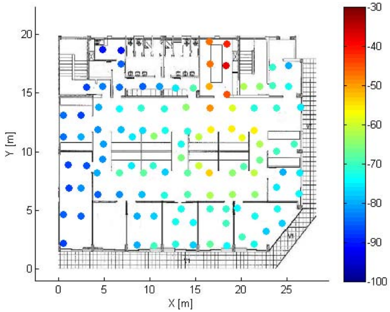


- AOA/TOA/TDOA measurements require additional hardware at the base stations or the mobile device
- RSS values are constantly monitored as part of the standard functionality for network operating reasons and can be easily collected through OS APIs

Indoor Signal Propagation

- Complex propagation conditions (multipath, shadowing) due to walls and ceilings



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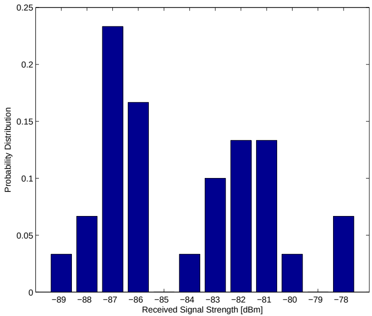

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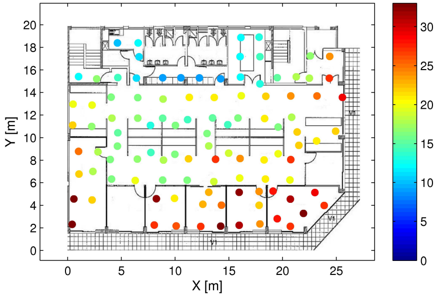

Indoor Signal Propagation

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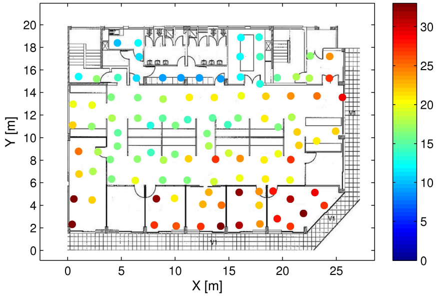
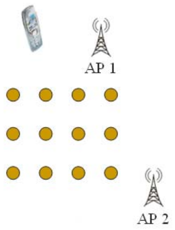
- Variable number of detected WiFi APs
- Unpredictable factors (people moving, doors, humidity)



Signal Strength Fingerprints

Fingerprint-based Positioning



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  - n APs deployed in the area
  - Fingerprints $r_i = [r_{i1}, \ldots, r_{in}]^T$
  - Averaging $\bar{r}_i = \frac{1}{M}\sum_{m=1}^{M} r_i(m)$
- **Online phase:** Positioning
  - Fingerprint $s = [s_1, \ldots, s_n]^T$ is observed
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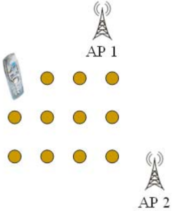

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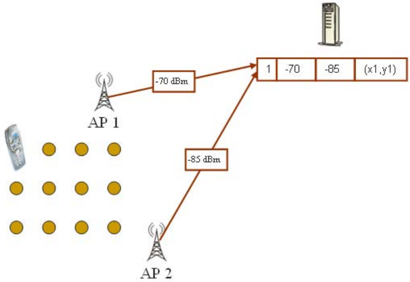

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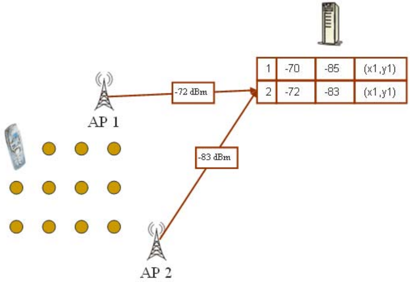

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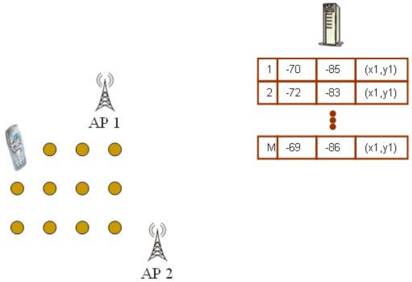

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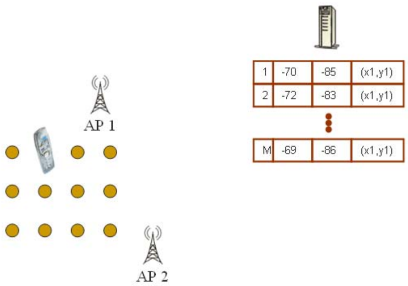

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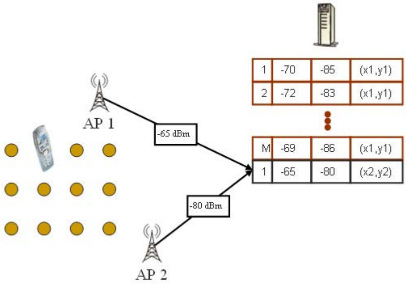

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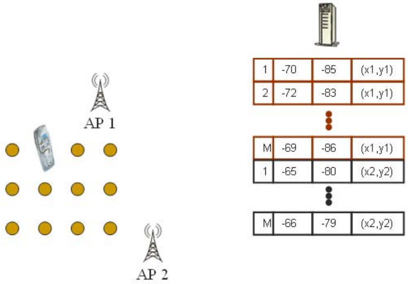

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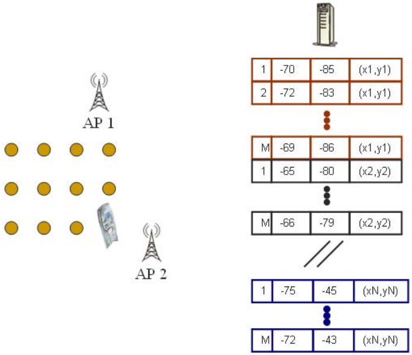

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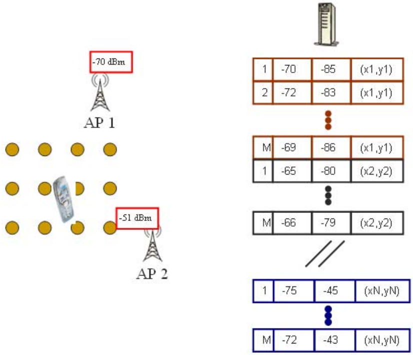

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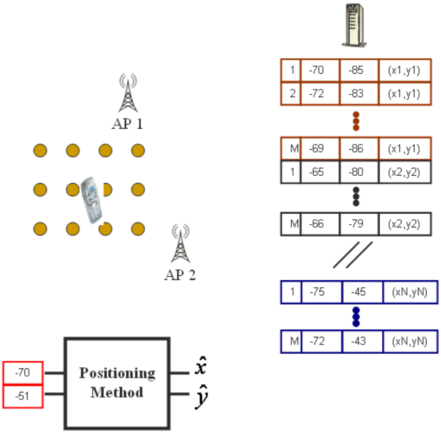
  - Fingerprint $s = [s_1, \ldots, s_n]^T$ is observed
  - Obtain an estimate $\widehat{\ell}$ using the radio map

Fingerprint-based Positioning



- **Offline phase:** Build RSS radio map
  - n APs deployed in the area
  - Fingerprints $r_i = [r_{i1}, \ldots, r_{in}]^T$
  - Averaging $\bar{r}_i = \frac{1}{M} \sum_{m=1}^{M} r_i(m)$
- **Online phase:** Positioning
  - Fingerprint $s = [s_1, \ldots, s_n]^T$ is observed
  - Obtain an estimate $\widehat{\ell}$ using the radio map

Deterministic Approach

Deterministic positioning methods

Location is estimated as a convex combination of the reference locations ℓ_i by using the K locations with the shortest distances between $\bar{r}_i$ and s.

$$\widehat{\ell} = \sum_{i=1}^{K} \frac{w_i}{\sum_{j=1}^{K} w_j} \ell'_i \tag{1}$$

where $\{\ell'_1, \ldots, \ell'_l\}$ denotes the ordering of reference locations with respect to increasing distance $\|\bar{r}_i - s\|$.

K-Nearest Neighbor (KNN) variants

- NN: $K = 1$
- KNN: $K \neq 1$, $w_i = \frac{1}{K}$
- Weighted KNN: $K \neq 1$, $w_i = \frac{1}{\|\bar{r}_i - s\|}$

Probabilistic Approach

Probabilistic positioning methods

Location ℓ is treated as a random vector that can be estimated by calculating the conditional probabilities $p(\ell_i|s)$ (*posterior*) given s.

$$p(\ell_i|s) = \frac{p(s|\ell_i)p(\ell_i)}{p(s)} = \frac{p(s|\ell_i)p(\ell_i)}{\sum_{i=1}^{l} p(s|\ell_i)p(\ell_i)} \quad (2)$$

$$p(s|\ell_i) = \prod_{j=1}^{n} p(s_j|\ell_i) \quad (3)$$

$p(s|\ell_i)$ is the *likelihood*, $p(\ell_i)$ is the *prior* and $p(s)$ is a constant.

Positioning variants

- Maximum Likelihood: $\widehat{\ell} = \arg\max_{\ell_i} p(s|\ell_i)$
- Maximum A Posteriori: $\widehat{\ell} = \arg\max_{\ell_i} p(s|\ell_i)p(\ell_i)$
- Minimum Mean Square Error: $\widehat{\ell} = \mathbf{E}[\ell|s] = \sum_{i=1}^{l} \ell_i p(\ell_i|s)$

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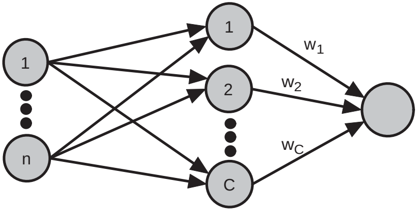
Radial Basis Function Networks

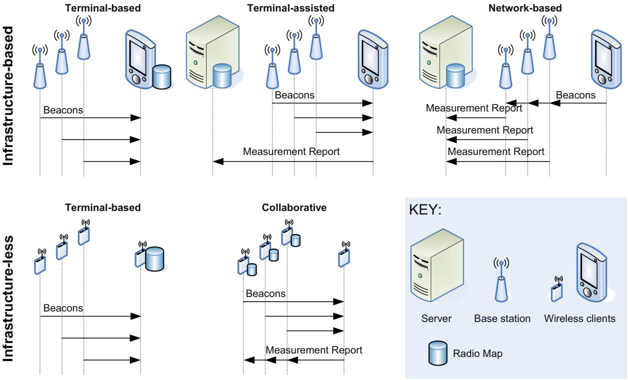


$$\ell(s) = \sum_{i=1}^{C} w_i u(s, c_i)$$

$$u(s, c_i) = \frac{\varphi(\|s - c_i\|)}{\sum_{j=1}^{C} \varphi(\|s - c_j\|)}$$

- C: number of centers
- c_i: n-dimensional center
- $\varphi(\|s - c\|) = \exp\left(-\frac{1}{2}\|s - c\|^2\right)$
- w_i: 2-dimensional weights

Positioning System Architectures



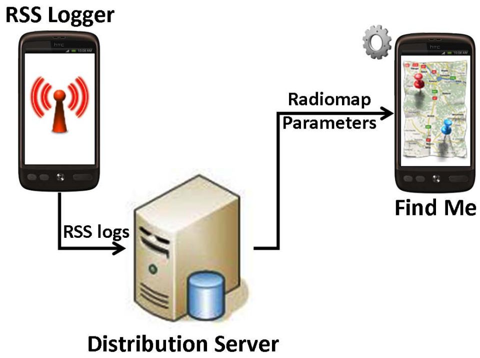
Mikkel Baun Kjærgaard, 2007

Airplace System

Terminal-based Infrastructure-assisted Architecture

- **Low Communication Overhead**: Avoids uploading the observed RSS fingerprint to the positioning server
- **User Privacy & Security**: Location is estimated by the user

http://www2.ucy.ac.cy/~laoudias/pages/platform.html



RSS Logger Application

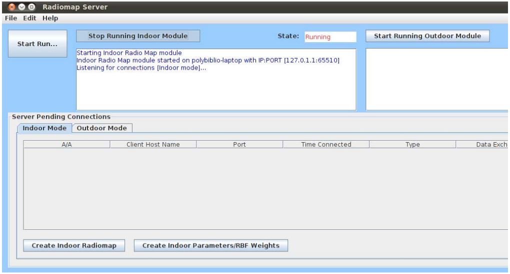
Facilitates collection and storage of the RSS data on the device.

- Developed around the Android RSS API for scanning and recording data samples in specific locations
- User-defined number of samples
- Users can contribute their data to Airplace for constructing and updating the radiomap through crowdsourcing

Distribution Server

Constructs the RSS radiomap and disseminates it to the requesting clients.

- Listens for connections from clients, that either contribute their RSS data or request the radiomap for positioning
- Parses all available RSS log files and merges them in a single compact radiomap file
- Fine tunes algorithm-specific parameters and stores them in a configuration file which is distributed with the radiomap



Find Me Application

Implements the positioning client running on the users device.

- Connects to the server for downloading the radiomap and algorithm-specific parameters
- Algorithm bank with several algorithms (KNN, MMSE, etc.)
- Dual Operation Mode: **Online** (real-time positioning) or **Offline** (evaluation of algorithms)

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Airplace Video Demonstration

Future lies Indoors

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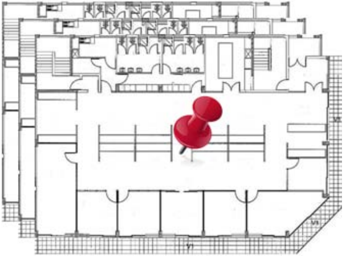
Future lies Indoors



- Moving from Google Maps to Google Floors!!

Thank you for your attention

Questions?

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