Location Determination

Framework and Technologies
Meaning of Location

- Three Dimensional Space
- Reference Coordinate System
  - Global – GPS
  - Local
  - Application Specific
- Multiple References
  - Ability to Map
- Notation
  - \( X = \{x, y, z\} \)
Location Uses

- All levels of accuracies have applications
- Outdoors
  - Navigation
    - Automobiles/Road Vehicles
    - Aircrafts
    - Boats/Ships
    - Personal – walking/jogging/running
  - Targetting
  - Finding Hospitals/Gas Stations….

- Indoors
  - Advertising
  - Finding …

- System based vs. device based
How

- Benchmarks
  - Known locations (Accuracy?)
  - Unknown Location WRT the location of Benchmarks
- What Form ??
  - Physical, marked locations
  - Location of devices
- What do I measure??
  - Proximity
  - Distance
  - Some function of distance
  - Direction
  - Some function of direction
- How many measurements
  - 3
  - 4
- Use Geometry
  - Triangulation
  - Trilateration
Desirable Features

- In Doors and Out Doors operation
- Independent of GPS
- Rapidly Deployable
- Agnostic to Frequency Band or Protocol
- Accurate
- Scalable
- ...

Proximity

- Detect the presence close to a known location
- RFID
  - Passive
    - Read by putting in a field of RF and reading the scatter pattern
    - Inventory Control
    - EZPass
  - Active
    - iBeacon
      - Using low power Bluetooth
    - Estimotes
    - ....
- How does Passive RFID approach compare with barcodes?
- FingerPrinting Based approach in WiFi Field
RF Field Based - WiFi

- AP – Generate Beacons 100 ms
- Can measure signal Strength
  - RSSI – Received Signal Strength Indicator
  - Included in spec to support handovers.
- RSSI – Relative scale or dbm
  - Most devices now report dbm
  - Range (-50 to -90 dbm)
  - Integer values only
Problem Formulation

- K Access Points
- Signal Field

\[ S(X) \]

Where \( S \) is \( k \) dimensional vector and \( X \) is the location vector.

- Problem – The signal strength of \( K \) APs is measured by a device as signal vector \( S \). Determine the location \( X \) where the device is

- Issues:
  - Is \( S \) an invertible function?
  - Does \( S \) have a closed form?
  - Is \( S \) deterministic or do the measurements vary with time
Signal Function

- Closed Form
  - Maxwell Equations
  - Affected by
    - Decay
    - Reflections
    - Refraction
    - Diffusion
    - Scattering
- Some Approximations have been attempted
- Outdoor – Cellular Phone
  - Accuracies ~200 meters
- Indoor – WiFi
  - Accuracies 5-10 meters

- What should be K, the number of signal generators – APs.
- Most WiFi deployment is for supporting networking access and not for location.
- At a location one can only hear a small number of APs.
  - There are ~4500 APs on campus. How do we efficiently handle this 4500 dimensional function?
Stochastic nature of Signals

- Repeated measurements vary when nothing has changed
- There is some correlation among samples
- Signal Vector has to be treated as a stochastic vector
- As it is reasonable to assume that all APs operate independently the signals from them can be treated as independent random variables.

- Analytical models require the modeling of the randomness
FingerPrinting

- We can estimate the joint probability distribution of the signal vector $p\{S(X)\}$ by empirical measurements
  - Discretize $X$ and make measurements of $S$ at known locations – a grid in $X$ space
  - Treat the measurement points as benchmark points
  - Find the benchmark point closest to the device signal vector in signal space

- May refine the location by determining a few closest benchmark points and interpolating
Horus: A WLAN-Based Indoor Location Determination System

Moustafa Youssef
WLAN Location Determination (Cont’d)

- Signal strength = $f(distance)$
- Does not follow free space loss
- Use lookup table = Radio map
- Radio Map: signal strength characteristics at selected locations
WLAN Location Determination (Cont’d)

- Offline phase
  - Build radio map
  - Radar system: average signal strength

- Online phase
  - Get user location
  - Nearest location in signal strength space (Euclidian distance)
Horus Goals

- High accuracy
  - Wider range of applications
- Energy efficiency
  - Energy constrained devices
- Scalability
  - Number of supported users
  - Coverage area
Sampling Process

- Active scanning
  - Send a probe request
  - Receive a probe response
Signal Strength Characteristics

- Temporal variations
  - One access point
  - Multiple access points

- Spatial variations
  - Large scale
  - Small scale
Temporal Variations
Temporal Variations

![Graph showing Temporal Variations](image-url)

- **Temporal Variations**
- **Average Signal Strength (dBm)**
- **Number of Samples Collected**
- **Receiver Sensitivity**

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<thead>
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<th>Average Signal Strength (dBm)</th>
<th>Number of Samples Collected</th>
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<td>-65</td>
<td>150</td>
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<td>-55</td>
<td>200</td>
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Receiver Sensitivity mark is at -85 dBm.
Temporal Variations: Correlation
Spatial Variations: Large-Scale

![Graph showing signal strength (in dbm) as a function of distance (in feet). The signal strength decreases as the distance increases, with a slight variation at around 30 feet.]
Spatial Variations: Small-Scale
Testbeds

- **A.V. William’s**
  - 4th floor, AVW
  - 224 feet by 85.1 feet
  - UMD net (Cisco APs)
  - 21 APs (6 on avg.)
  - 172 locations
  - 5 feet apart
  - Windows XP Prof.

- **FLA**
  - 3rd floor, 8400 Baltimore Ave
  - 39 feet by 118 feet
  - Linksys/Cisco APs
  - 6 APs (4 on avg.)
  - 110 locations
  - 7 feet apart
  - Linux (kernel 2.5.7)
  - Orinoco/Compaq cards
Horus Components

- Basic algorithm [Percom03]
- Correlation handler [InfoCom04]
- Continuous space estimator [Under]
- Locations clustering [Percom03]
- Small-scale compensator [WCNC03]
Basic Algorithm: Mathematical Formulation

- x: Position vector
- s: Signal strength vector
  - One entry for each access point
- s(x) is a stochastic process
- P[s(x), t]: probability of receiving s at x at time t
- s(x) is a stationary process
  - P[s(x)] is the histogram of signal strength at x
Basic Algorithm: Mathematical Formulation

- \( \text{Argmax}_x[P(x/s)] \)
- Using Bayesian inversion
  - \( \text{Argmax}_x[P(s/x).P(x)/P(s)] \)
  - \( \text{Argmax}_x[P(s/x).P(x)] \)
- \( P(x) \): User history
Basic Algorithm

- Offline phase
  - Radio map: signal strength histograms
- Online phase
  - Bayesian based inference
WLAN Location Determination (Cont’d)

\[ P(-53/L1) = 0.55 \]

\[ P(-53/L2) = 0.08 \]
Basic Algorithm:
Signal Strength Distributions
Basic Algorithm: Results

- Accuracy of 5 feet 90% of the time
- Slight advantage of parametric over non-parametric method
  - Smoothing of distribution shape
Correlation Handler

- Need to average multiple samples to increase accuracy
- Independence assumption is wrong
Correlation Handler: Autoregressive Model

- \( s(t+1) = \alpha s(t) + (1 - \alpha) v(t) \)
- \( \alpha \): correlation degree
- \( E[v(t)] = E[s(t)] \)
- \( \text{Var}[v(t)] = (1 + \alpha)/(1 - \alpha) \text{Var}[s(t)] \)
Correlation Handler: Averaging Process

- \( s(t+1) = \alpha s(t) + (1 - \alpha) v(t) \)
- \( s \sim N(0, m) \)
- \( v \sim N(0, r) \)
- \( A = \frac{1}{n} (s_1 + s_2 + \ldots + s_n) \)
- \( E[A(t)] = E[s(t)] = 0 \)
- \( \text{Var}[A(t)] = \frac{m^2}{n^2} \left\{ \left[ \frac{(1 - \alpha^n)}{(1 - \alpha)} \right]^2 + \frac{n + 1 - \alpha^2}{1 - \alpha^2} \cdot \frac{(1 - \alpha^{2(n-1)})}{(1 - \alpha^2)} \right\} \)
Correlation Handler: Averaging
Correlation Handler: Results

- Independence assumption: performance degrades as n increases
- Two factors affecting accuracy
  - Increasing n
  - Deviation from the actual distribution
Continuous Space Estimator

- Enhance the discrete radio map space estimator
- Two techniques
  - Center of mass of the top ranked locations
  
- Time averaging

\[
\bar{x} = \frac{\sum_{i=1}^{\min(N,||\bar{X}||)} p(i) \cdot \bar{X}(i)}{\min(N,||\bar{X}||) \sum_{i=1}^{\min(N,||\bar{X}||)} p(i)}
\]

\[
\bar{x}_t = \frac{1}{\min(W, t)} \cdot \sum_{t-\min(W, t)+1}^{t} x_i
\]
Center of Mass: Results

- $N = 1$ is the discrete-space estimator
- Accuracy enhanced by more than 13%
Time Averaging Window: Results

- $N = 1$ is the discrete-space estimator
- Accuracy enhanced by more than 24%
Horus Components

- Basic algorithm
- Correlation handler
- Continuous space estimator
- Small-scale compensator
- Locations clustering
Small-scale Compensator

- Multi-path effect
- Hard to capture by radio map (size/time)
Small-scale Compensator: Small-scale Variations

- Variations up to 10 dBm in 3 inches
- Variations proportional to average signal strength
Small-scale Compensator: Perturbation Technique

- Detect small-scale variations
  - Using previous user location
- Perturb signal strength vector
  - \((s_1, s_2, \ldots, s_n) \rightarrow (s_1 \pm d_1, s_2 \pm d_2, \ldots, s_n \pm d_n)\)
  - Typically, \(n=3-4\)
- \(d_i\) is chosen relative to the received signal strength
**Small-scale Compensator: Results**

- Perturbation technique is not sensitive to the number of APs perturbed
- Better by more than 25%
Horus Components

- Basic algorithm
- Correlation handler
- Continuous space estimator
- Small-scale compensator
- Locations clustering
Locations Clustering

- Reduce computational requirements
- Two techniques
  - Explicit
  - Implicit

![Graph showing the relationship between Number of Samples Collected and Average Signal Strength (dBm) with Receiver Sensitivity indicated.](image)
Locations Clustering: Explicit Clustering

- Use access points that cover each location
- Use the $q$ strongest access points

$S = [-60, -45, -80, -86, -70]$

$S = [-45, -60, -70, -80, -86]$

$q = 3$
Locations Clustering: Results- Explicit Clustering

- An order of magnitude enhancement in avg. num. of oper. /location estimate
- As q increases, accuracy slightly increases
Locations Clustering: Implicit Clustering

- Use the access points incrementally
- Implicit multi-level clustering

$S = \{-60, -45, -80, -86, -70\}$

$S = \{-45, -60, -70, -80, -86\}$
Locations Clustering: Results - Implicit Clustering

- Avg. num. of oper. /location estimate better than explicit clustering
- Accuracy increases with Threshold
Horus Components

- Horus System Components
  - Location API
  - Applications
    - Signal Strength Acquisition API
    - Estimated Location
    - Device Driver (MAC, Signal Strength)

- Horus Components
  - Discrete-Space Estimator
  - Continuous-Space Estimator
  - Small-Scale Compensator
  - Correlation Handler
  - Clustering
  - Correlation Modeler
  - Radio Map Builder
  - Radio Map and Clusters
  - Correlation Modeler
  - Clustering
  - Signal Strength Acquisition API
  - Device Driver
Horus-Radar Comparison

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<th>Stdev</th>
<th>Max</th>
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<tbody>
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<td>Horus (basic)</td>
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<td>Radar</td>
<td>9.74</td>
<td>13.15</td>
<td>10.71</td>
<td>57.67</td>
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</table>
Training Time

- 15 seconds training time per location
Radio map Spacing

- Average distance error increase by as much as 100% (20 feet)
- 14 feet gives good accuracy
Radar with Horus Techniques

- Average distance error enhanced by more than 58%
- Worst case error decreased by more than 76%
Conclusions

- The *Horus* system achieves its goals
- High accuracy
  - Through a probabilistic location determination technique
  - Smoothing signal strength distributions by Gaussian approximation
  - Using a continuous-space estimator
  - Handling the high correlation between samples from the same access point
  - The perturbation technique to handle small-scale variations
- Low computational requirements
  - Through the use of clustering techniques
Conclusions (Cont’d)

- Scalability in terms of the coverage area
  - Through the use of clustering techniques
- Scalability in terms of the number of users
  - Through the distributed implementation
- Training time of 15 seconds per location is enough to construct the radio-map
- Radio map spacing of 14 feet
- Horus vs. Radar
  - More accurate by more than 11 feet, on the average
  - More than an order of magnitude savings in number of operations required per location estimate
- Horus vs. Ekahau
Conclusions (Cont’d)

- Modules can be applied to other WLAN location determination systems
  - Correlation handling, continuous-space estimator, clustering, and small-scale compensator

- Applied to Radar
  - Average distance error enhanced by more than 58%
  - Worst case error decreased by more than 76%

- Techniques presented thesis are applicable to other RF-technologies
  - 802.11a, 802.11g, HiperLAN, and BlueTooth, …
Locus

- Indoor location anywhere on College Park Campus
- Based on Wi-Fi RSSI
- ~ 4500 Access Points
- Floor accuracy >95%
- Location Accurate to the room
- Being integrated with M-Urgency
Flying Turtle
Locating indoors
Flying Squirrel – NRL Project

- **Goal**
  - Real-time discovery, analysis, and mapping of IEEE 802.11a/b/g/n wireless networks
  - Use passive listeners
  - Extensive analytics
Flying Turtle

- 20 sensors on 4100 wing of AVW
  - compose approx. 20 ft, 20 ft grid points.
Initial Observations
Our Approach

- Dynamic Fingerprinting/Radio Map
- With passive listeners
  - Can we provide accurate localization from measured signal strengths?
Time Based Location

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Director, MIND Lab
Professor, Computer Science
University of Maryland
Topics

- Location Determination
  - Horus and Locus
  - PinPoint
- Clock Synchronization
  - With Absolute Real Time
GeoLocation

- RSSI Based – Horus and Locus
- Accurate Time Stamping
- GeoLocation with accuracy in inches
- Clock Synchronization
  - Mapping Function Timing Protocol
  - Synchronization with Absolute Time
- Flying Turtle - testbed
PinPoint Technology - Basis

- Use a clock model
- Determine node to node distance by measuring time of flight of the signal
The clock at a node is assumed to have drift stable over short periods.

Hence clock time $\tau$ is related to the real time $t$ by

$$\tau_a(t) = \beta_a (\alpha_a + t)$$

where

- $\alpha$ and $\beta$ remain constant for the measurement phase.
- $\beta$, the drift rate of the clock is no worse than 100 parts per million
- $\tau$ is measured with a nanosecond resolution
Measurements for node pair A and B

Let

\( \tau_a1, \tau_b1 \): tx and rx ts of first A msg
\( \tau_b2, \tau_a2 \): tx and rx ts of first B msg
\( \tau_a3, \tau_b3 \): tx and rx ts of second A msg
\( \tau_a4, \tau_b4 \): tx and rx ts of second B msg
Calculations for node pair A and B

• Drift ratio

\[
\frac{\tau_{a3} - \tau_{a1}}{\tau_{b3} - \tau_{b1}} = \frac{\beta_a (\alpha_a + t_3) - \beta_a (\alpha_a + t_1)}{\beta_b (\alpha_b + t_3 + d) - \beta_b (\alpha_b + t_1 + d)} = \frac{\beta_a}{\beta_b}
\]

• Propagation delay

\[
\beta_{a1} = \frac{(\tau_{b1} - \tau_{a1}) + (\tau_{a2} - \tau_{b2})}{2} + \frac{1}{2} \left( \frac{\beta_a}{\beta_b} - 1 \right) (\tau_{a2} - \tau_{a1})
\]

\[
\tau_b(t) = \tau_{b1} - \beta_b d - \frac{\beta_b}{\beta_a} \tau_{a1} + \frac{\beta_a}{\beta_b} \tau_a(t)
\]

\[
t = \frac{\tau_a(t)}{\beta_a} - \alpha_a
\]
Accurate Time-stamping

- Accuracy of distance measurement is directly related to the accuracy of timestamping
- Collaboration with Austrian Academy of Sciences
  - SMiLE 3 board
Figure 2. Block diagram of SMiLE PCB
SMiLE Details

- Altera FPGA Cyclone III
- Max 2830 WiFi chip
- Sampling Rate = 44 MHz (22.75 nsTick)
- Discretization 256 levels (22.75/256 = 88.77 ps)
Measurement Results

- **Time Stamping**
  - Tick time 88.77 ps (~2.66 cm)
  - Standard Deviation of Error – 0.97 ticks
  - Stable

- **Clocks**
  - Have variable drifts (~0.119 to 0.364 ppm)
Clock Drift (Skew)
Distance Measurements

- Configuration

![Configuration Image]
Distance Measurements

- Configuration
  - Outdoors

- Experiment
  - Nodes take turn is sending messages
  - 10ms interval

![Diagram of distance measurements](attachment:image_url)
## Distance Statistics

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Implication

- ASIC Based Technique with accuracy in inches with sub second latencies
- Indoor Location
  - Multipath Effects need addressing
Clock Synchronization

- Mapping Function Based
- With Absolute Time
Mapping Function Based Synchronization

- Normal approach
  - Exchange signals
  - Determine corrections
  - Correct the local clock

- Our Approach
  - Use a free running local clock
  - Exchange messages to determine a mapping function
  - When time information is needed
    - Read time from local clock
    - Map it using a mapping function
Mapping Function

- Two nodes, a and b
- \( \varphi_a(t) = t_a \)
- \( \psi_a(t_a) = t \)
  - Example

\[ \tau_a(t) = \beta_a(\alpha_a + t) \]

- \( \varphi_{ab}(t_b) = t_a \)
- \( \psi_{ab}(t_a) = t_b \)
Approach

- Linear model of clock works well over short periods of time
- When exchanging messages, Time instants $t_a(2)$ and $t_b(2)$ are the same time instants in real time.
- Calculate and use a piecewise linear mapping function
Synchronization tolerance

- How far is the time at a node compared to the mapped time?
Synchronization Tolerance

- 3 nodes 4 ft apart
- Average ~ 80 ps, STD ~ 60 ps
Synchronization Tolerance

- Five Nodes – 123451 path
Synchronization with Absolute time

- Note that
  \[
  \beta_b d = \left( \tau_{b1} - \tau_{a1} \right) + \left( \tau_{a2} - \tau_{b2} \right) + \frac{1}{2} \left( \frac{\beta_a}{\beta_b} - 1 \right) \left( \tau_{a2} - \tau_{a1} \right)
  \]

- If we can measure \( d \) accurately we can determine \( \beta \) the drift rate with respect to real time
Two Approaches

- **Over the air**
  - The term \( d \) is a function of distance and the speed of light.
    - We can keep nodes at fixed distance
    - Speed of light through air changes as a function of temperature, pressure and humidity
    - Monitoring these we can determine the speed of light with an accuracy of one part in \( 10^9 \)
    - As these parameters change slowly we can have a stable reference during a mission.

- **Using a communications means with known delay**
  - Fiber with measured delay