Horus: A WLAN-Based Indoor Location Determination System

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Motivation

- Ubiquitous computing is increasingly popular
- Requires
  - Context information: location, time, …
  - Connectivity: 802.11b, Bluetooth, …
- Location-aware applications
  - Location-sensitive billing
  - Tourist services
  - Asset tracking
  - E911
  - Security
  - …

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Location Determination Technologies

- GPS
- Cellular-based
- Ultrasonic-based: Active Bat
- Infrared-based: Active Badge
- Computer vision: Easy Living
- Physical proximity: Smart Floor
- Not suitable for indoor
  - Does not work
  - Require specialized hardware
  - Scalability

WLAN Location Determination

- Triangulate user location
  - Reference point
  - Quantity proportional to distance
- WLAN
  - Access points
  - Signal strength= *f(distance)*
- Software based

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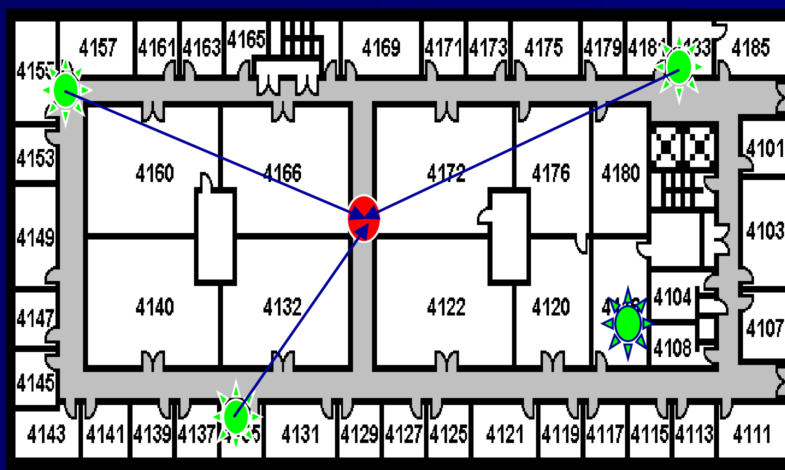
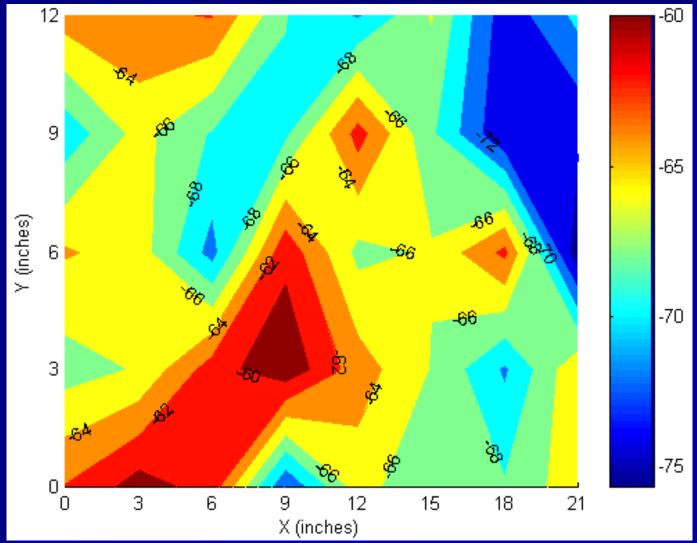
Roadmap

- ✓ Motivation
- ✓ Location determination technologies
- ➢ **Introduction**
- Noisy wireless channel
- Horus components
- Performance evaluation
- Conclusions and future work

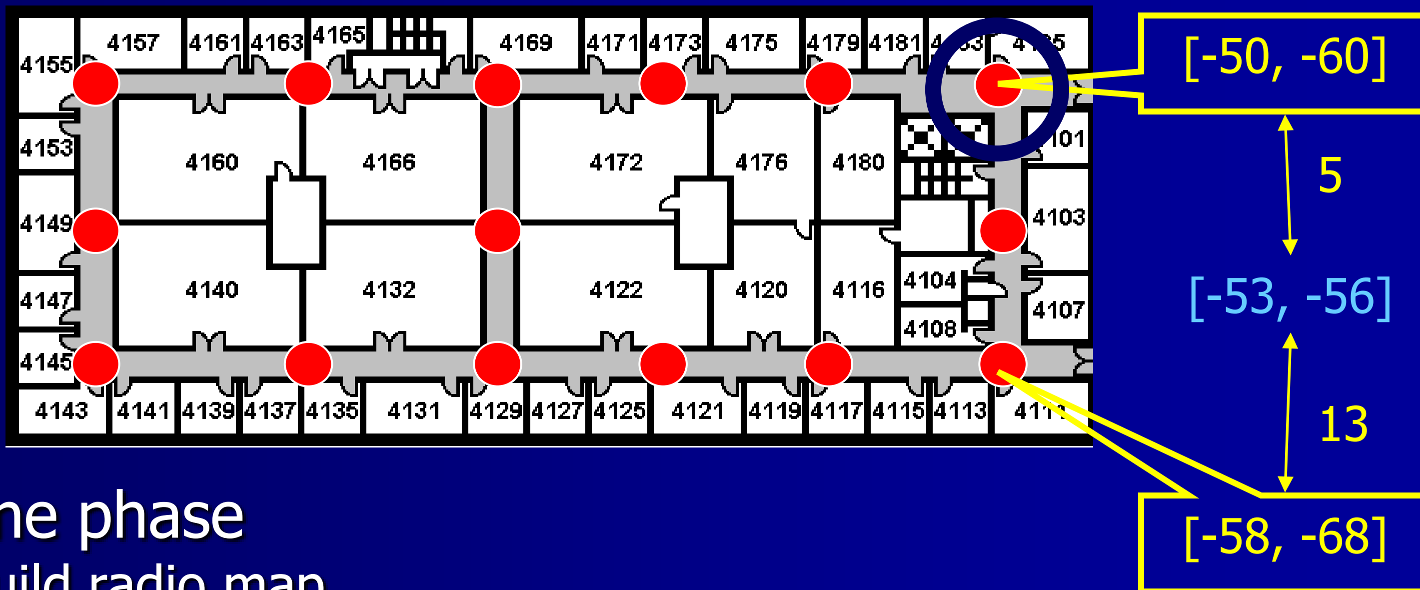
WLAN Location Determination (Cont'd)





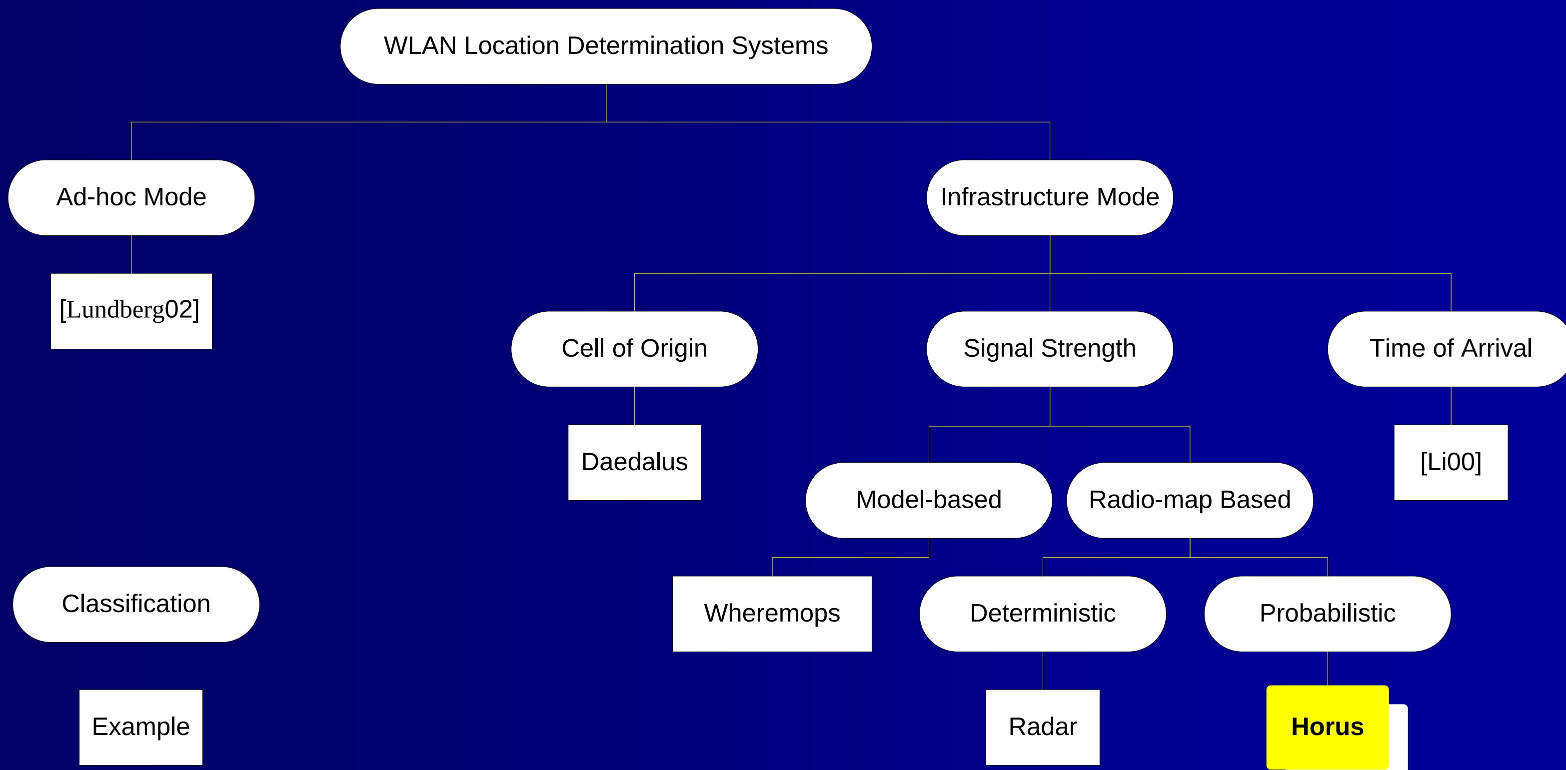
- Signal strength= *f(distance)*
- Does not follow free space loss
- Use lookup table ≡ **Radio map**
- Radio Map: signal strength characteristics at selected locations

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)

WLAN Location Determination Taxonomy



Horus Goals

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

Contributions

- Taxonomy of WLAN location determination systems
- Modeling the signal strength distributions using parametric and non-parametric distributions
- Handling correlation between successive samples from the same access point
- Allowing continuous space estimation
- Clustering of radio map locations
- Handling small-scale variations
- Compare the performance of the *Horus* system with other systems

Roadio-map

- ✓ Motivation
- ✓ Location determination technologies
- ✓ Introduction
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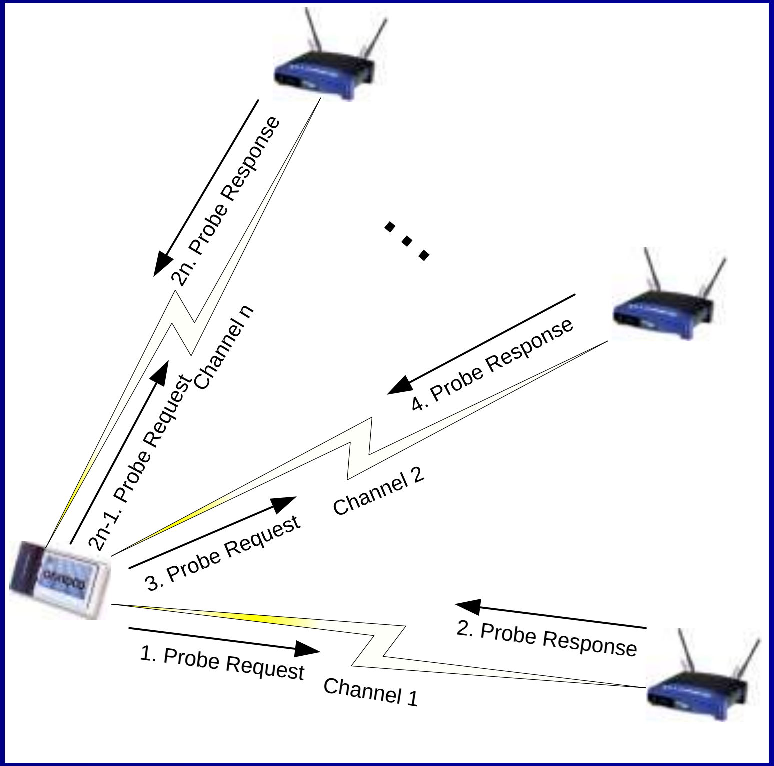
Sampling Process

- Active scanning
  - Send a probe request
  - Receive a probe response



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Signal Strength Characteristics

- Temporal variations
  - One access point
  - Multiple access points
- Spatial variations
  - Large scale
  - Small scale

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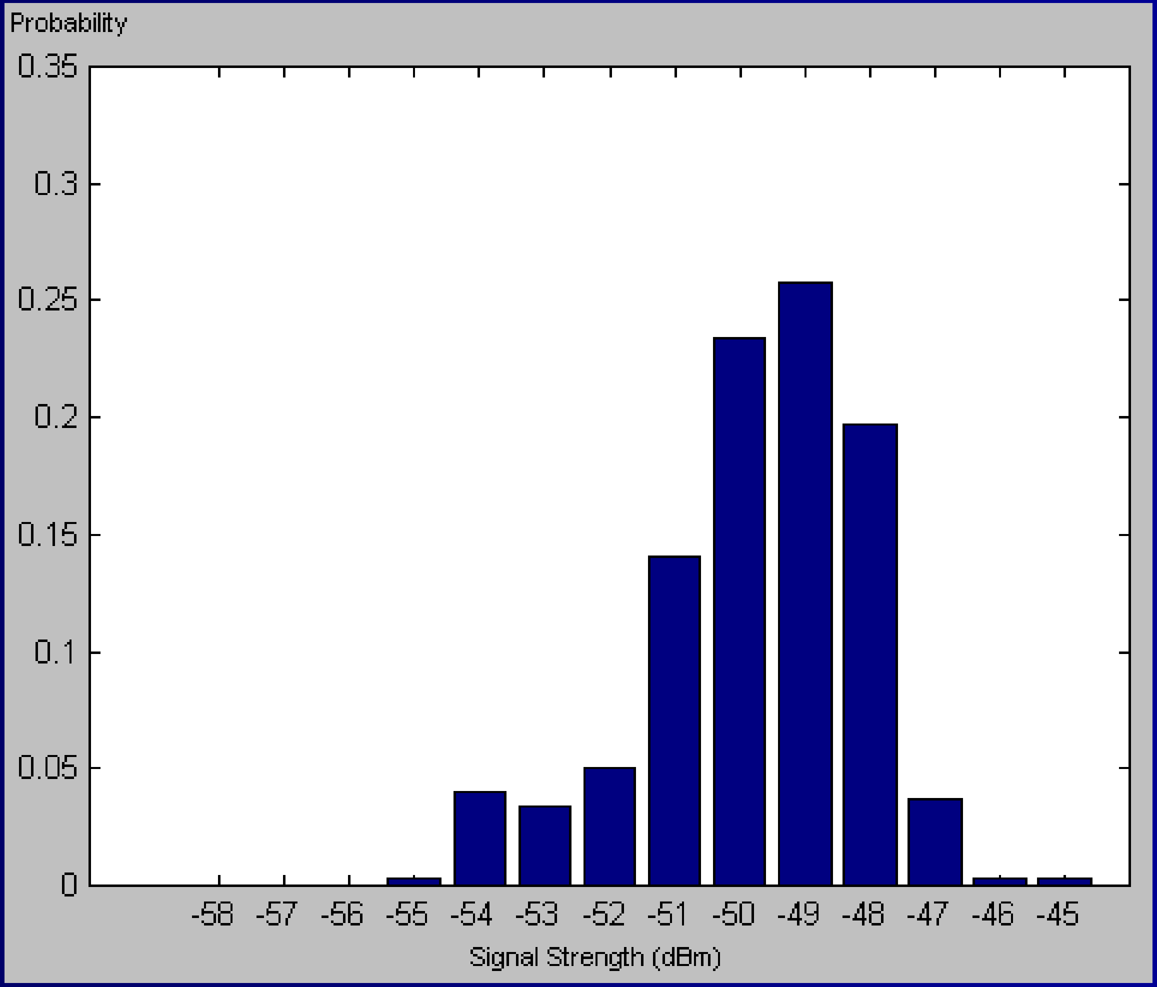
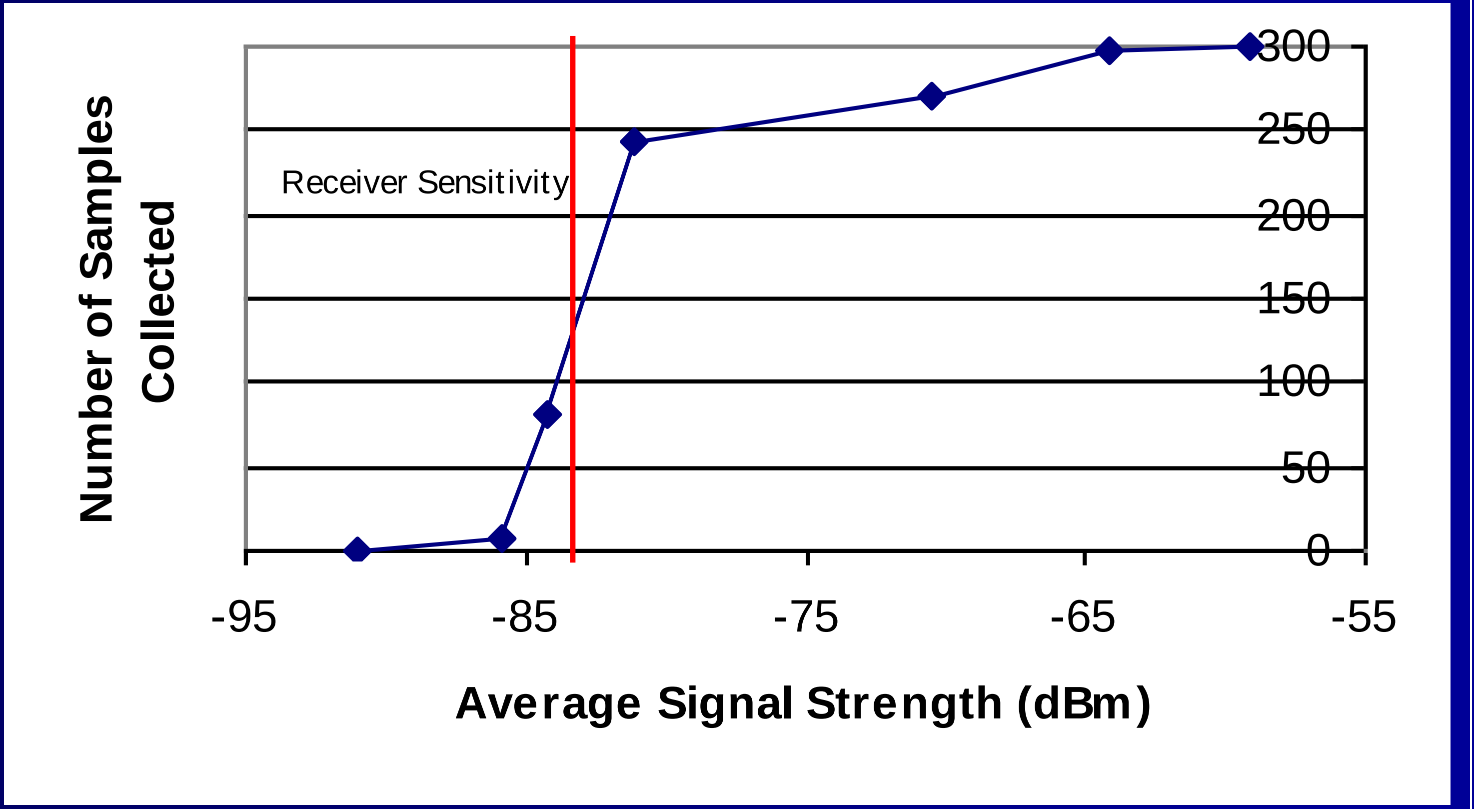
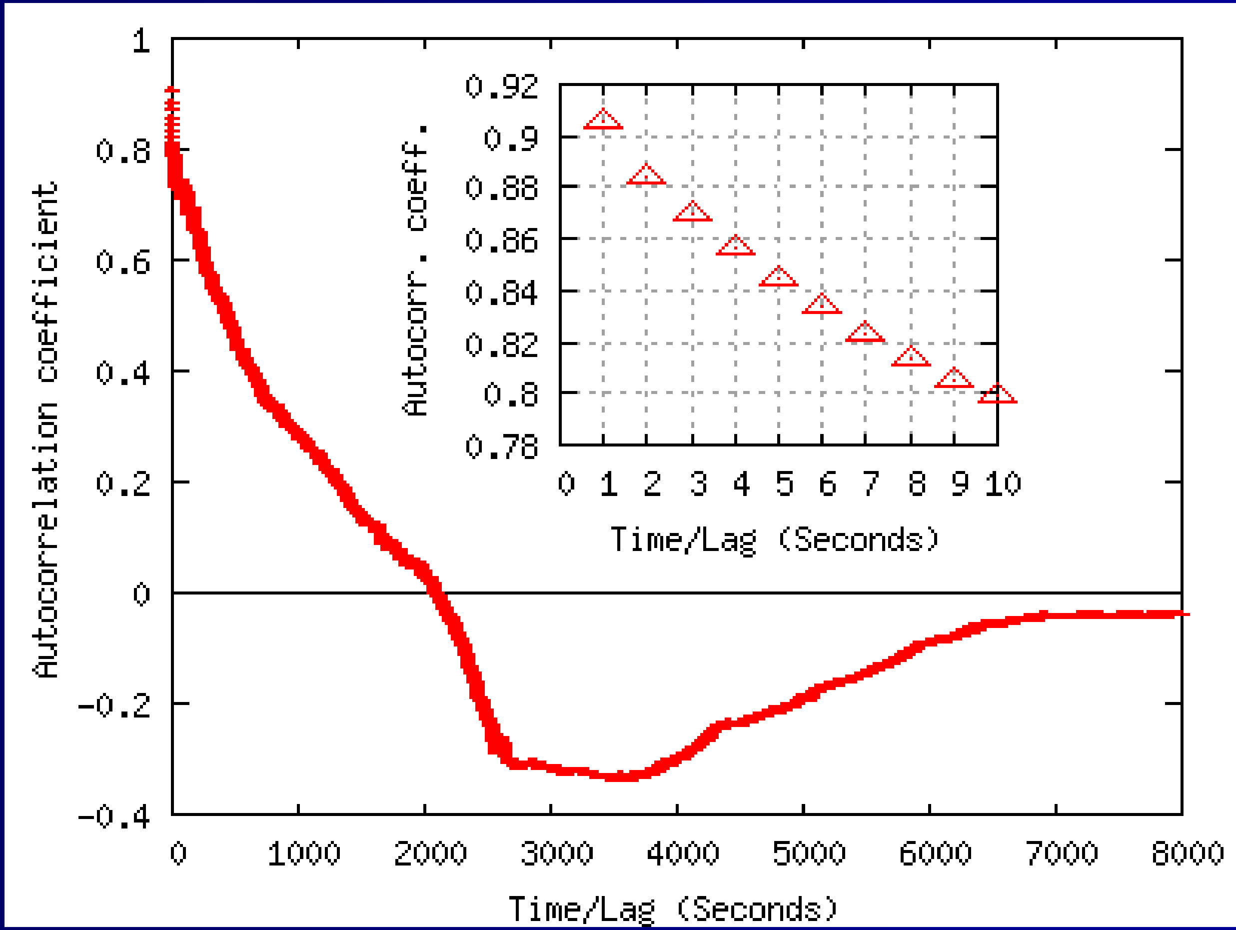
Temporal Variations



Temporal Variations



Temporal Variations: Correlation



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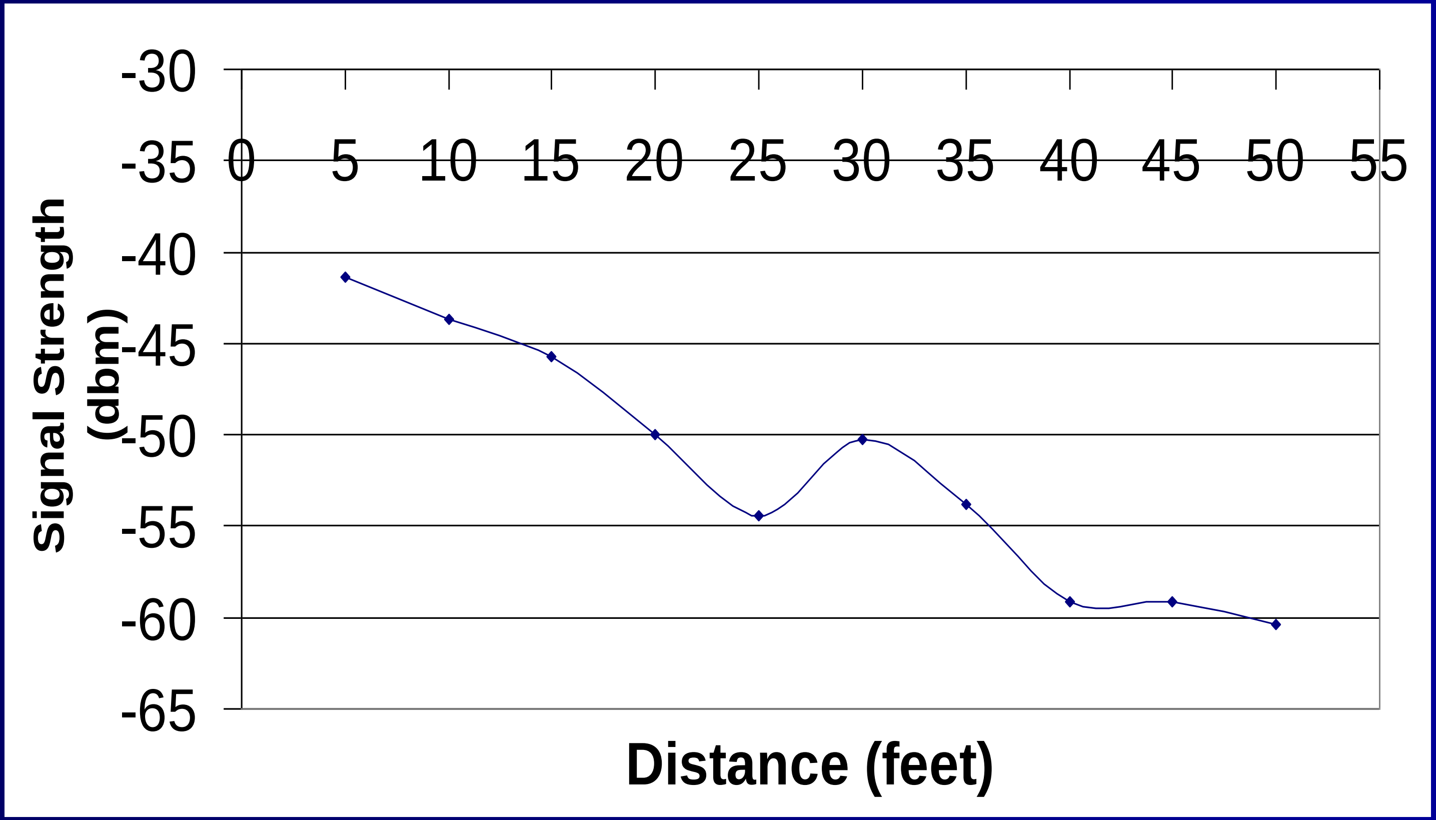
Spatial Variations: Large-Scale



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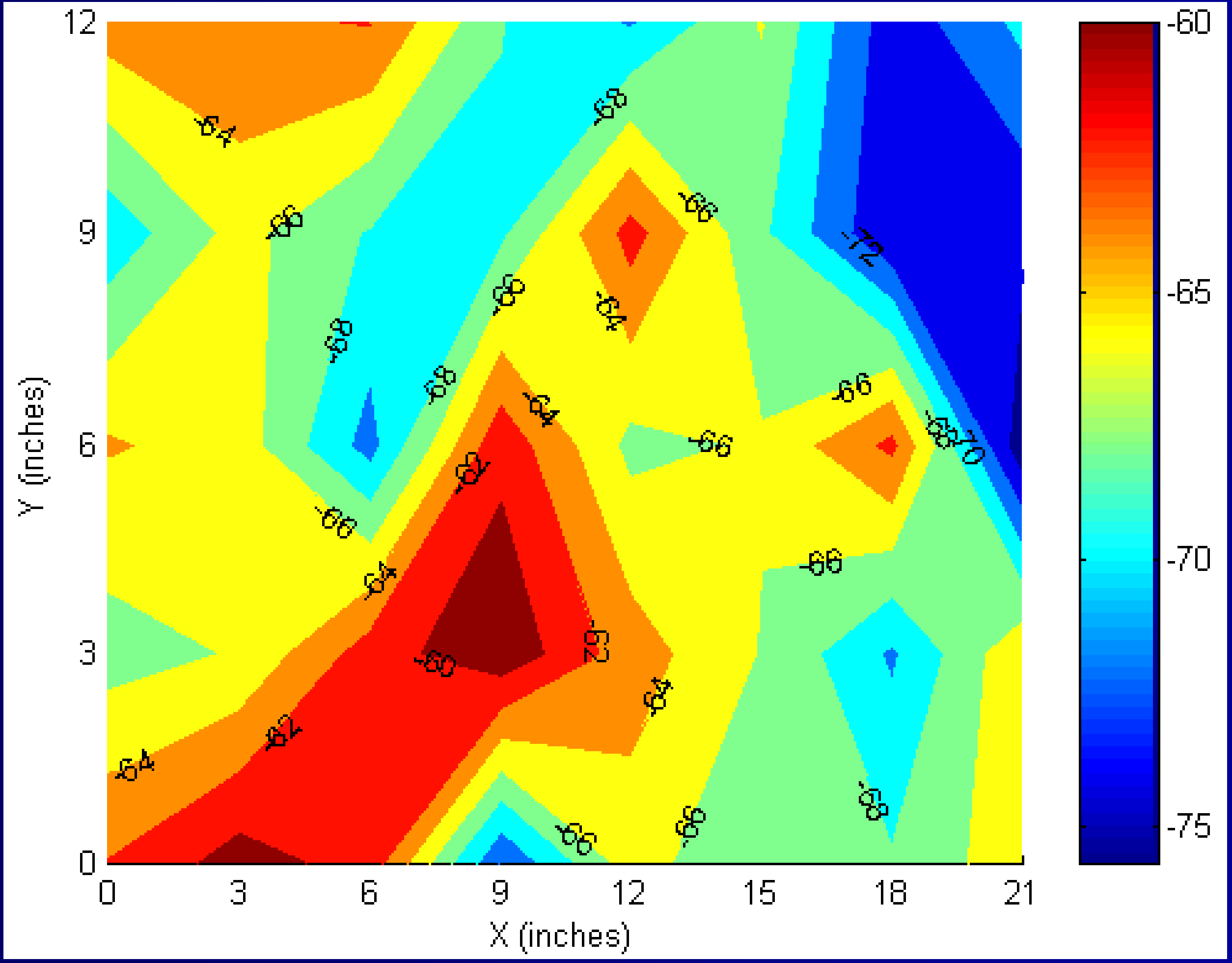
Spatial Variations: Small-Scale



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Roadio-map

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- ✓ Goals
- ✓ Introduction
- ✓ Noisy wireless channel
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Testbeds

- A.V. William's
  - 4^{th} 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

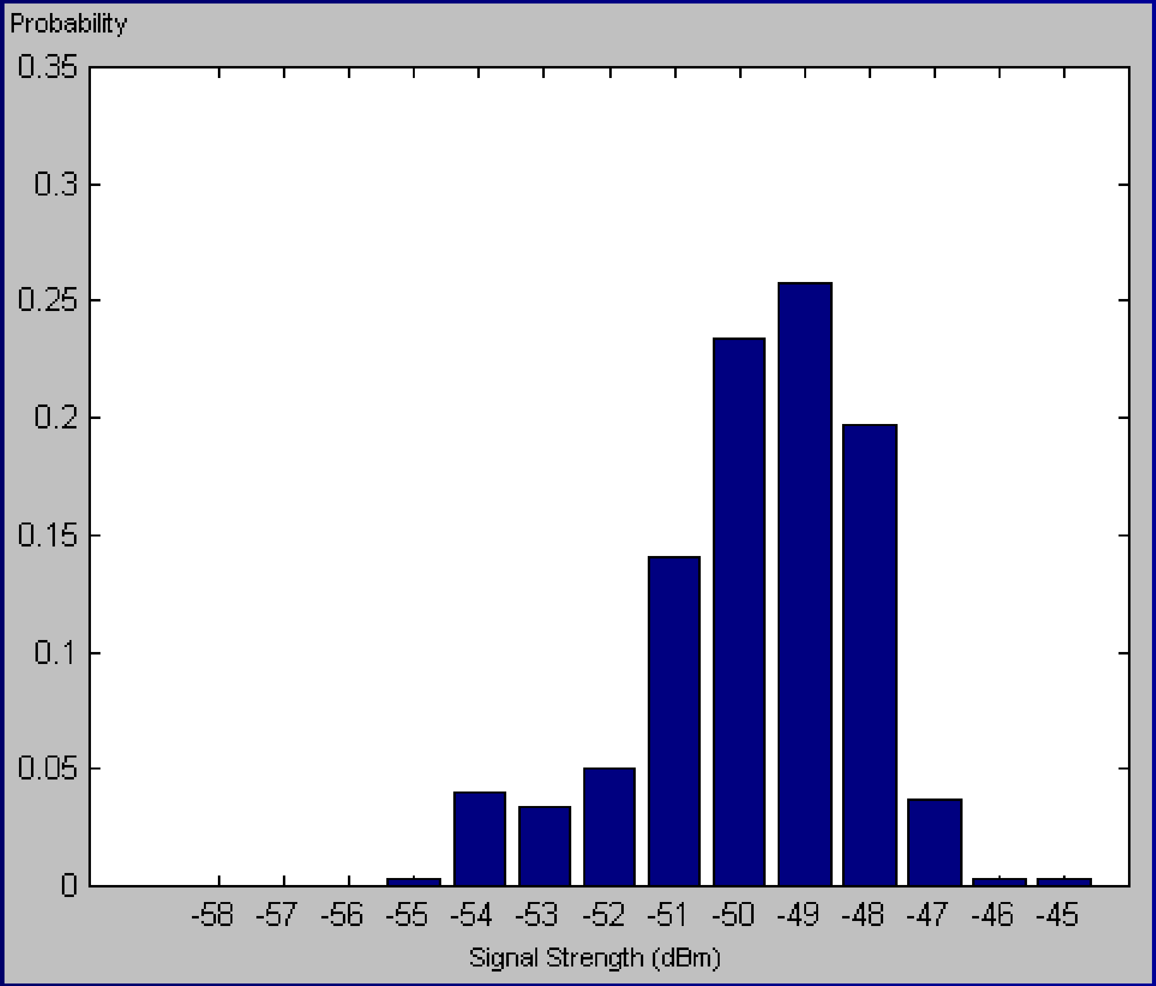
Horus Components

- 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



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

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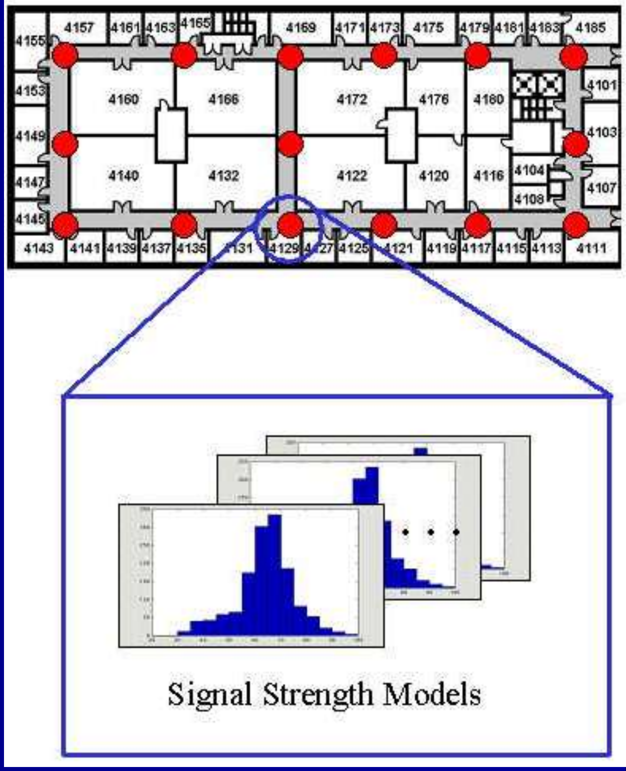
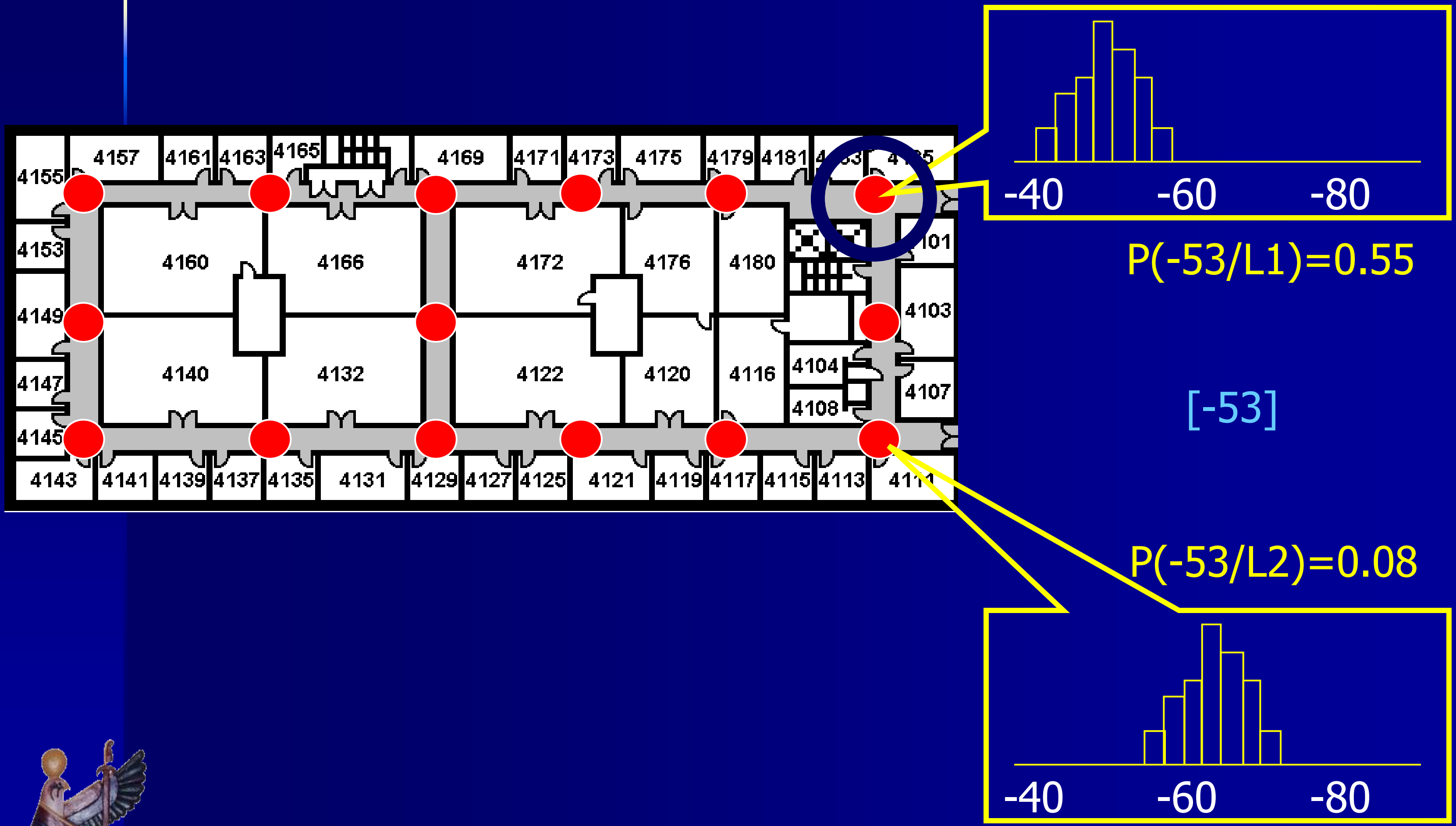
Basic Algorithm

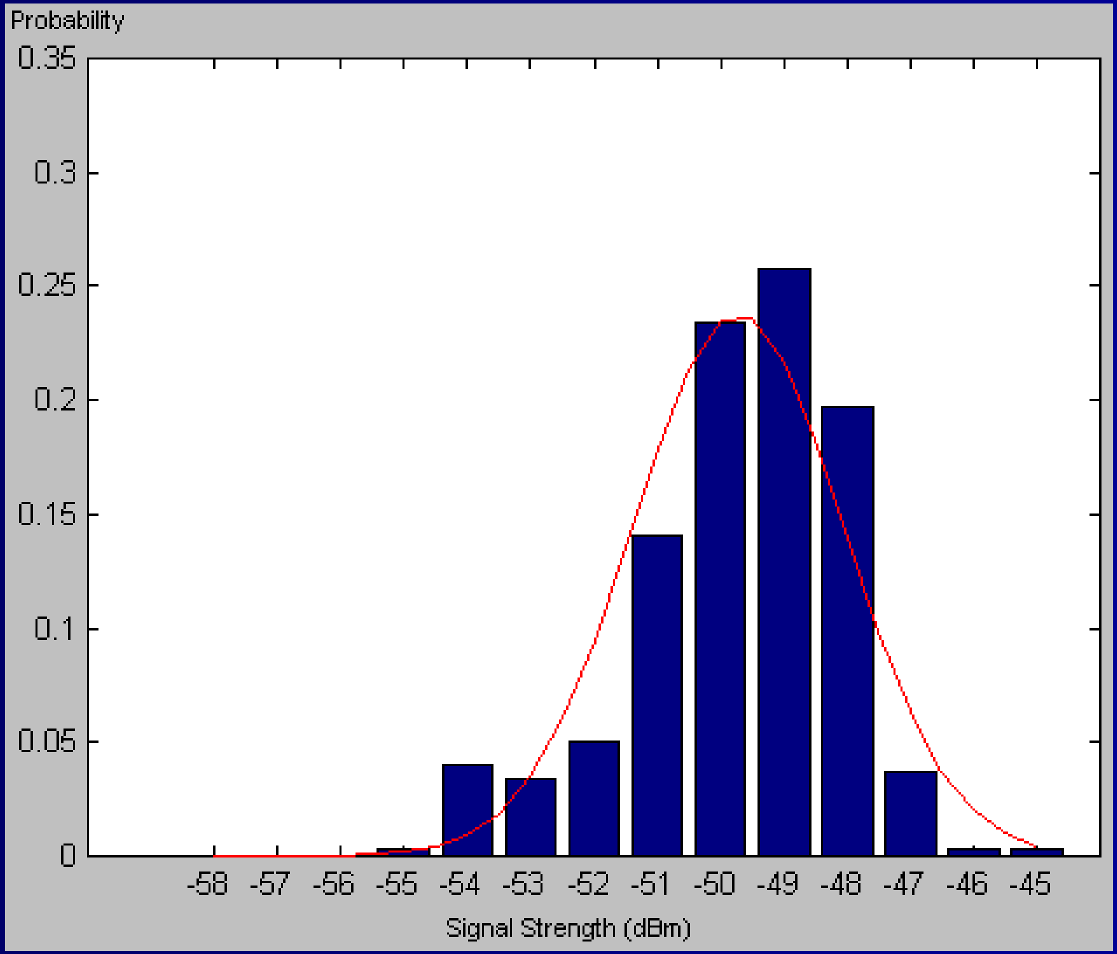
- Offline phase
  - Radio map: signal strength histograms
- Online phase
  - Bayesian based inference



WLAN Location Determination (Cont'd)



Basic Algorithm: Signal Strength Distributions



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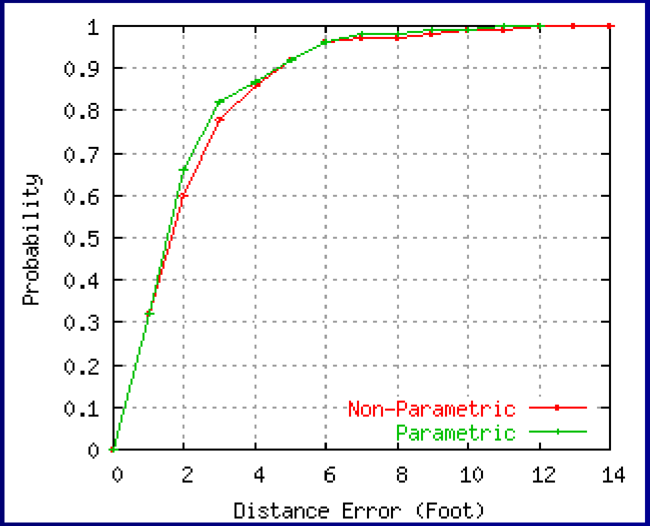
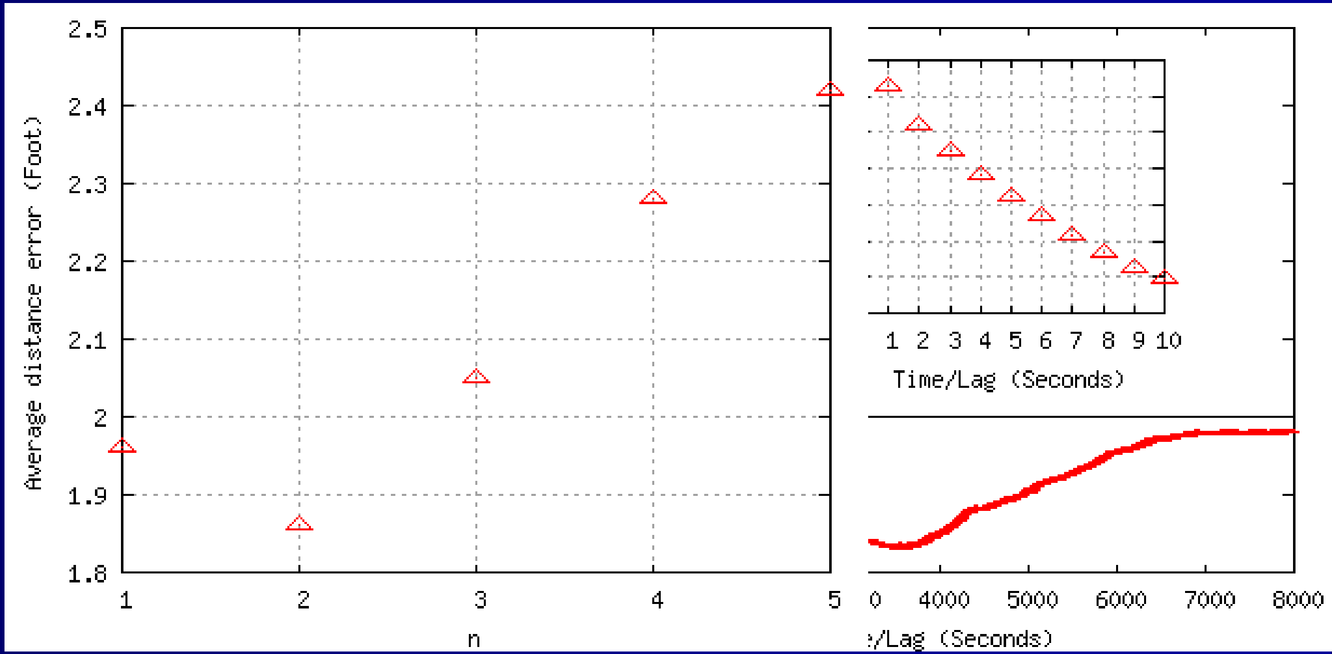
Basic Algorithm: Results



- 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

- $s(t+1)=\alpha.s(t)+(1-\alpha).v(t)$
- α: correlation degree
- $E[v(t)]=E[s(t)]$
- $Var[v(t)]= (1+\alpha)/(1-\alpha)\ Var[s(t)]$

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Correlation Handler: Averaging Process

- $s(t+1) = \alpha . s(t) + (1-\alpha) . v(t)$
- $s \sim N(0, m)$
- $v \sim N(0, r)$
- $A = 1/n \, (s_1 + s_2 + \ldots + s_n)$
- $E[A(t)] = E[s(t)] = 0$
- $Var[A(t)] = m^2/n^2 \{ [(1-\alpha^n)/(1-\alpha)]^2 + n + 1 - \alpha^2 * (1-\alpha^{2(n-1)})/(1-\alpha^2) \}$

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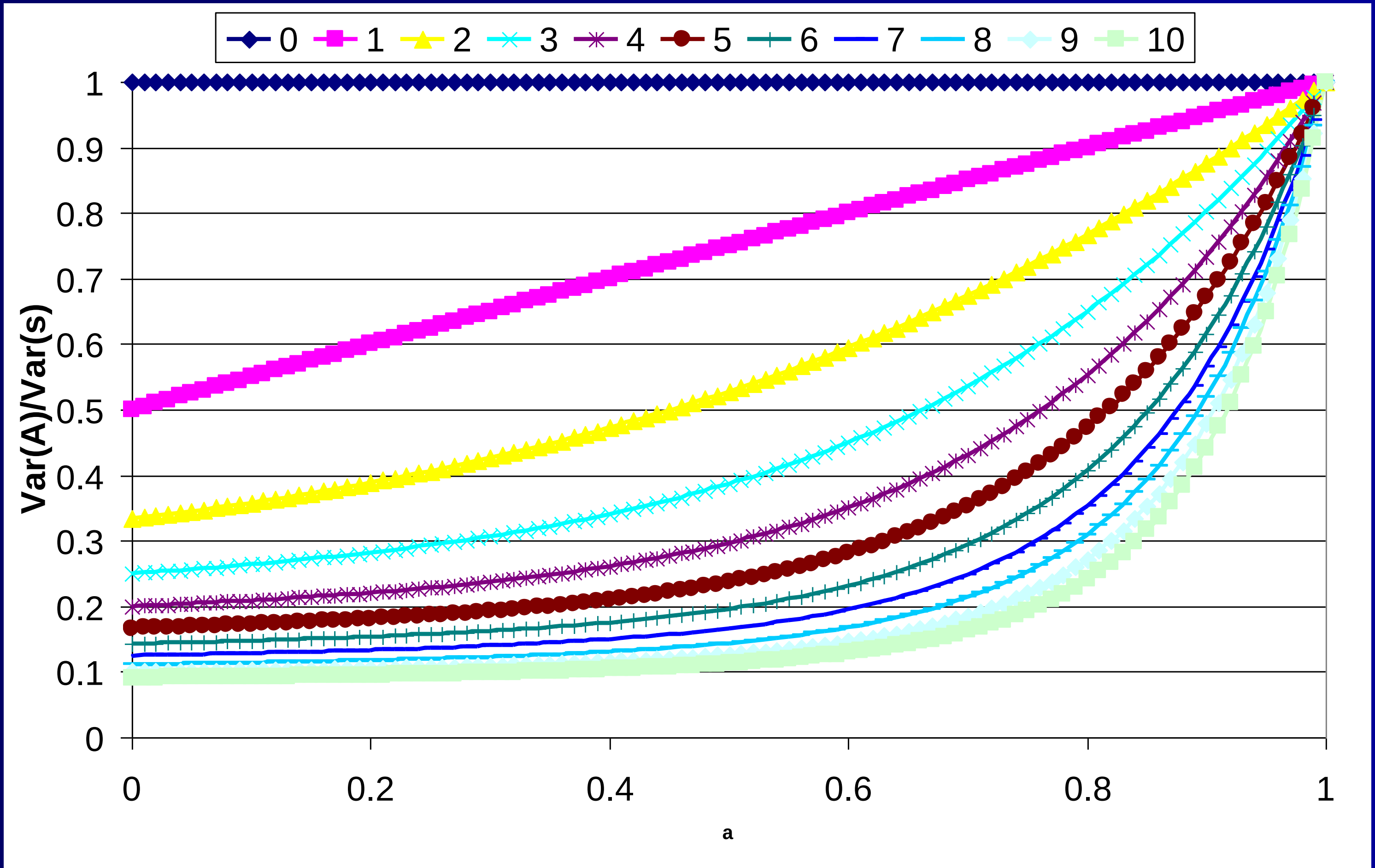
Correlation Handler: Averaging



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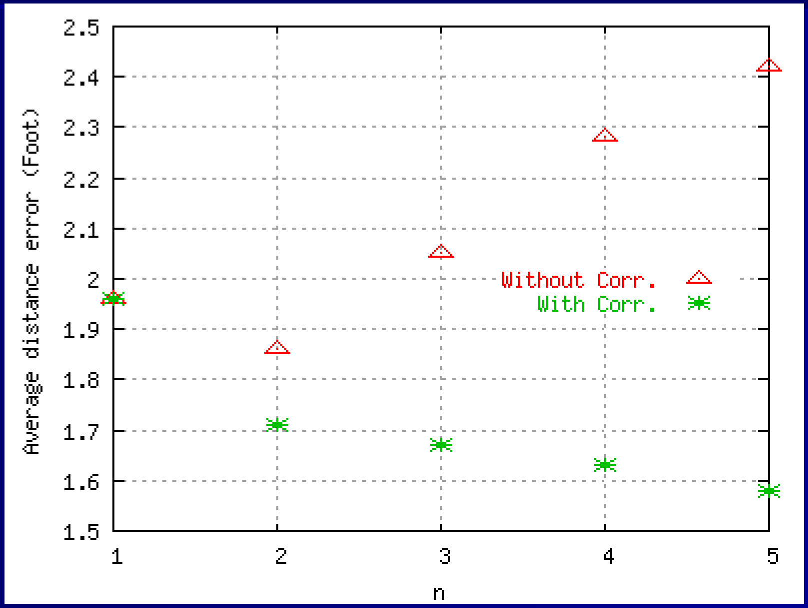
Correlation Handler: Results



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

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Continuous Space Estimator

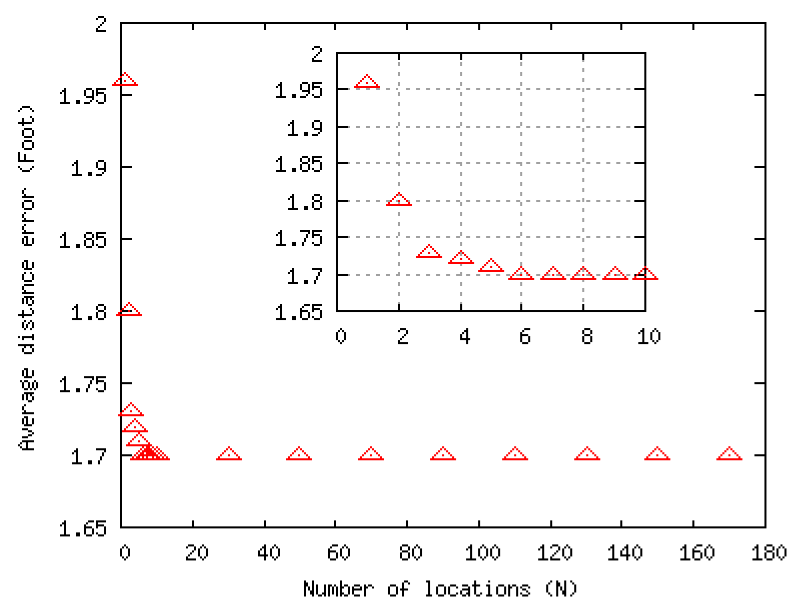
- Enhance the discrete radio map space estimator
- Two techniques
  - Center of mass of the top ranked locations

$$x \leftarrow \frac{\sum_{i=1}^{\min(N,\|\bar{\mathbb{X}}\|)} p(i) * \bar{\mathbb{X}}(i)}{\sum_{i=1}^{\min(N,\|\bar{\mathbb{X}}\|)} p(i)}$$

  - Time averaging window

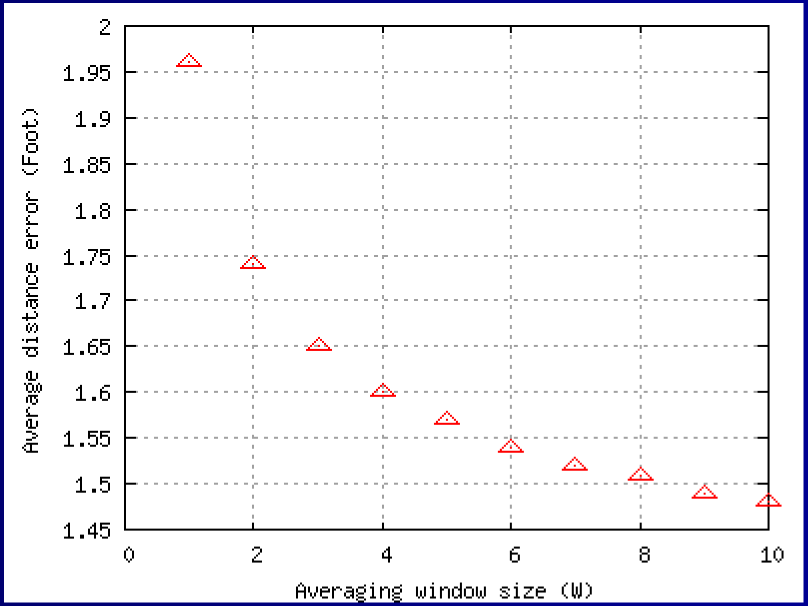
$$\bar{x}_t = \frac{1}{\min(W,t)} \cdot \sum_{t-\min(W,t)+1}^{t} x_i$$

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%

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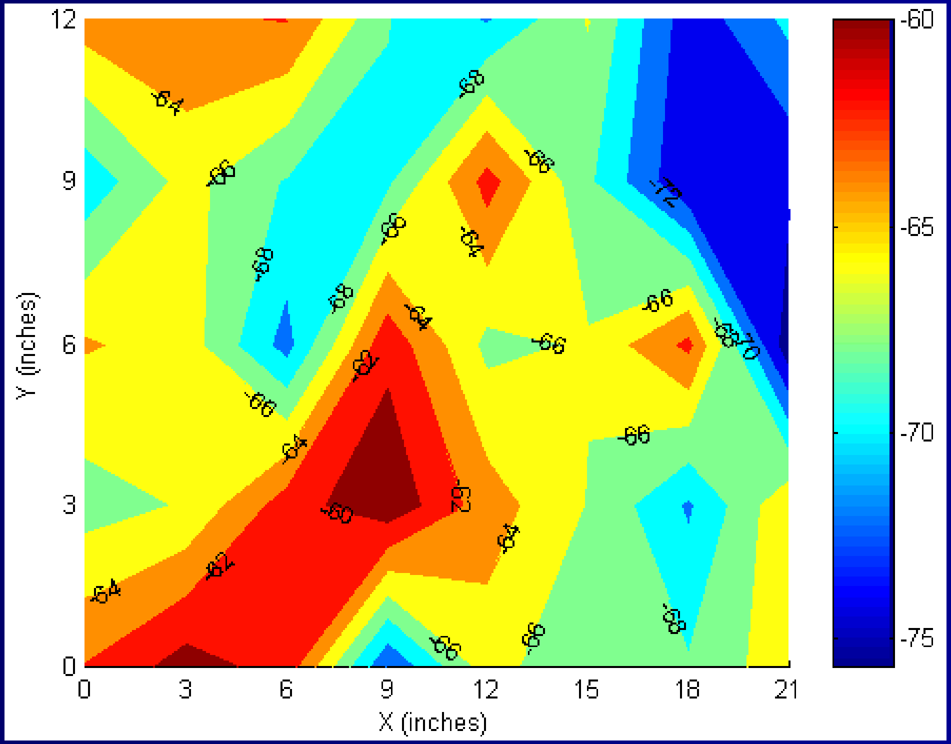
Horus Components

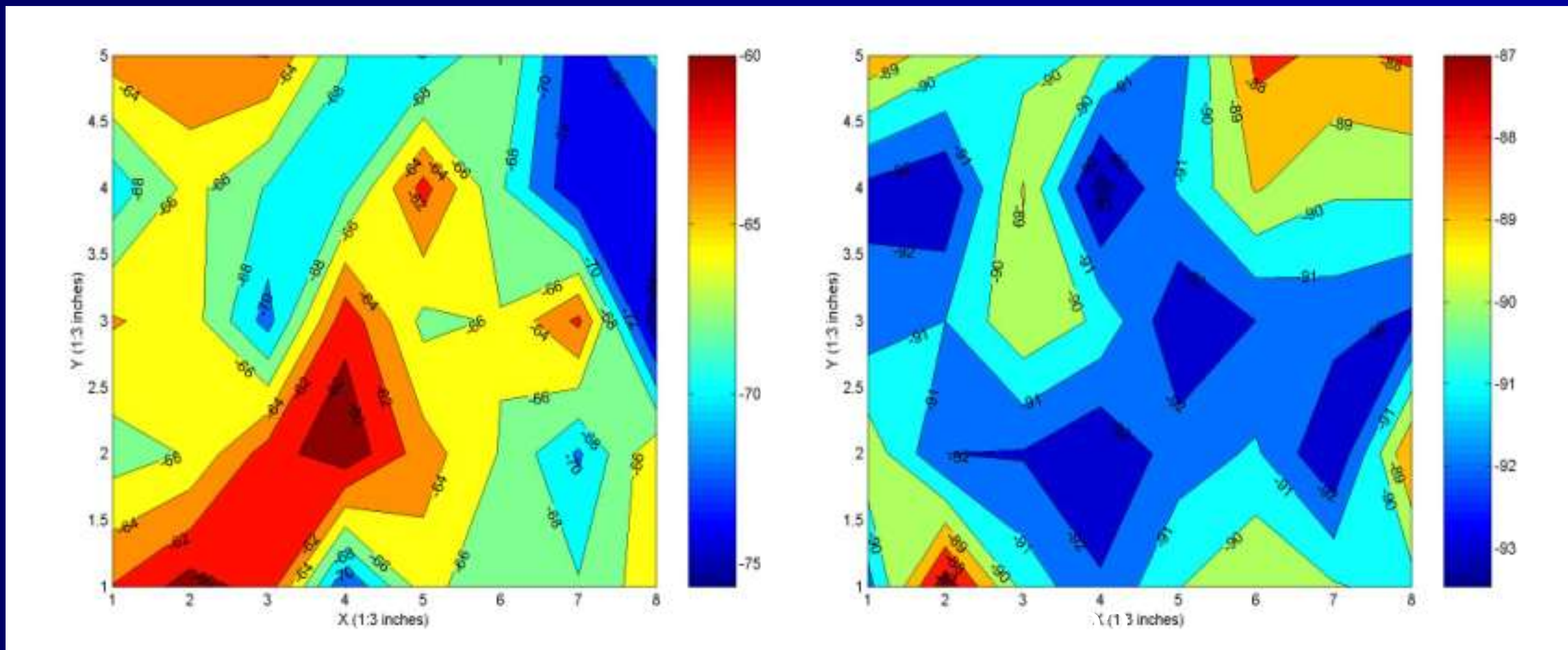
- Basic algorithm
- Correlation handler
- Continuous space estimator
- Small-scale compensator
- Locations clustering

Small-scale Compensator



- Multi-path effect
- Hard to capture by radio map (size/time)

Small-scale Compensator: Small-scale Variations

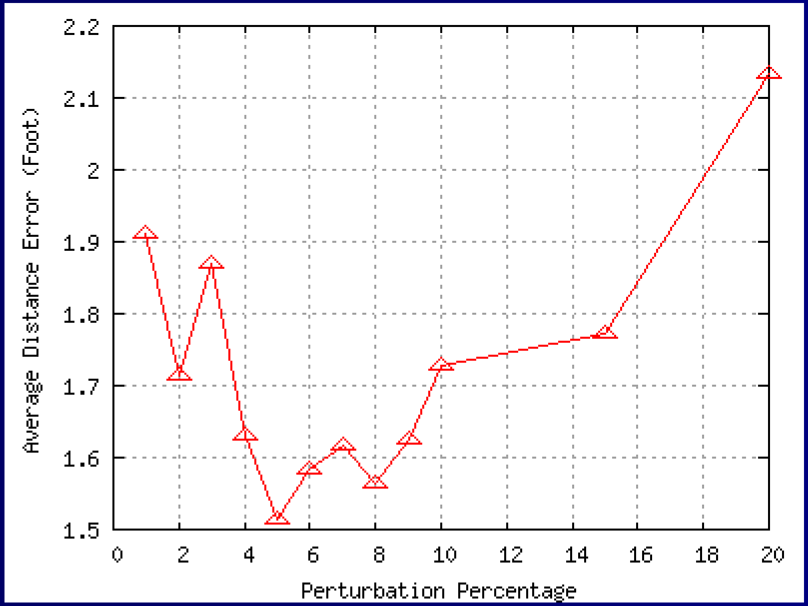


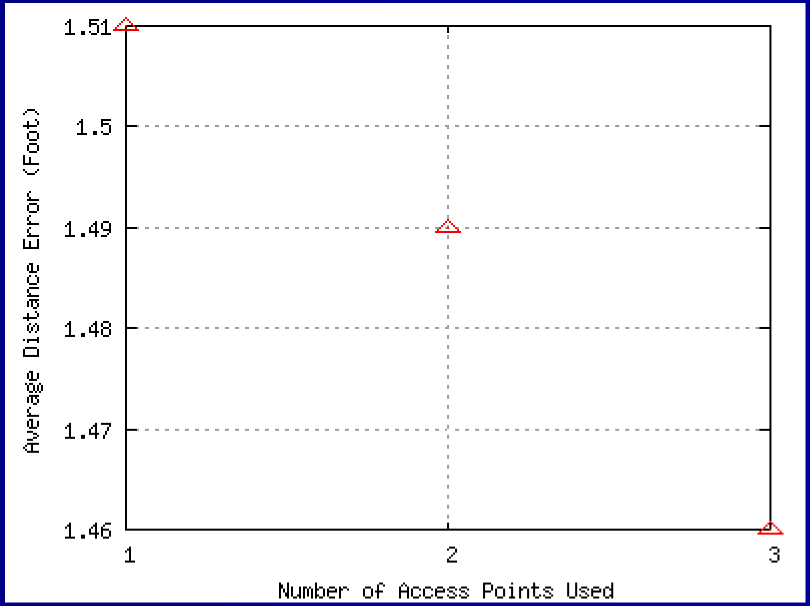
- Variations up to 10 dBm in 3 inches
- Variations proportional to average signal strength

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%

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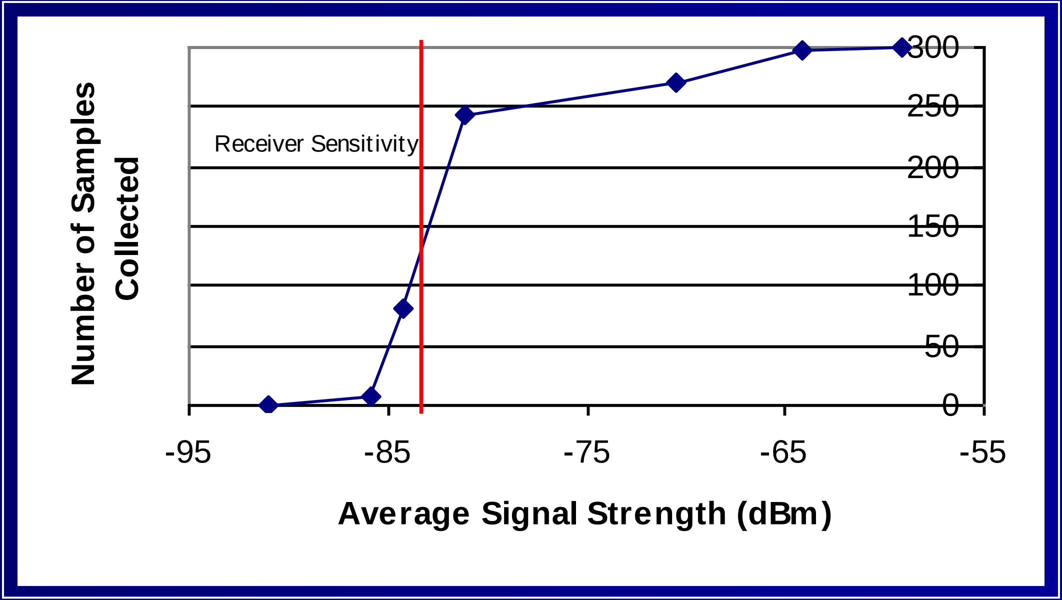
Horus Components

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

Locations Clustering

- Reduce computational requirements
- Two techniques
  - Explicit
  - Implicit

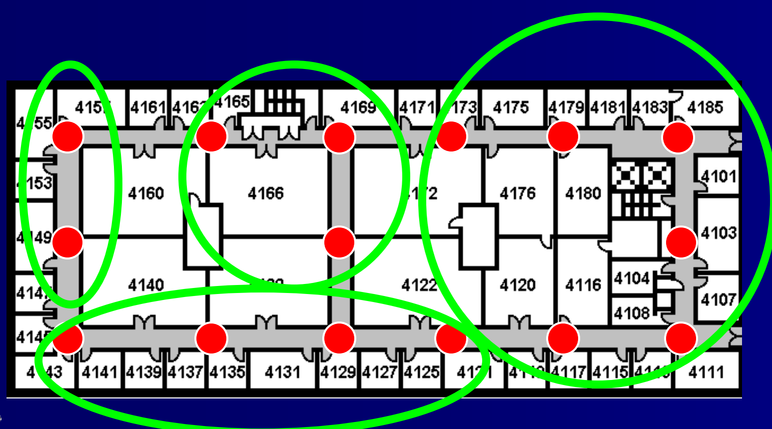


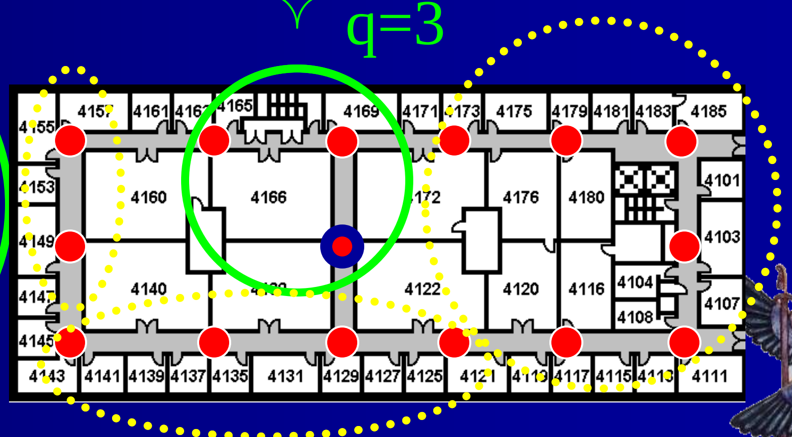
Locations Clustering: Explicit Clustering

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

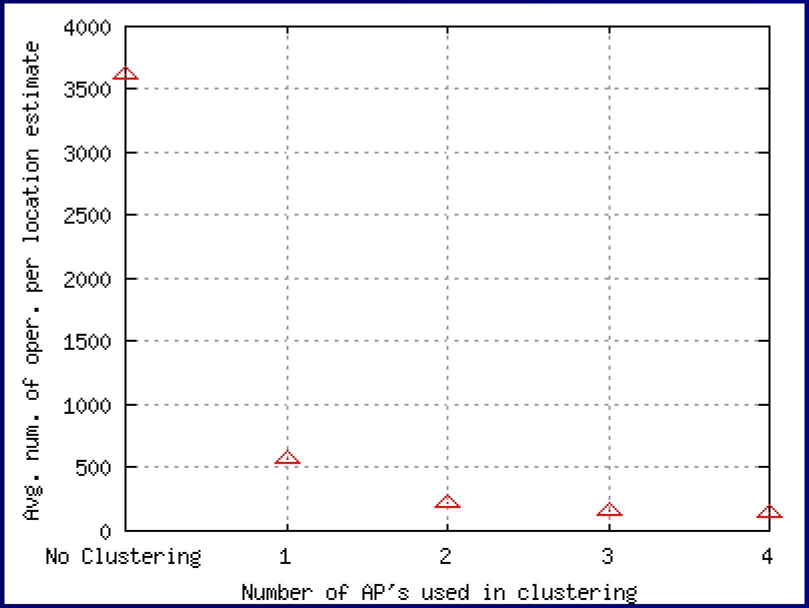
S=[-60, -45, -80, -86, -70]

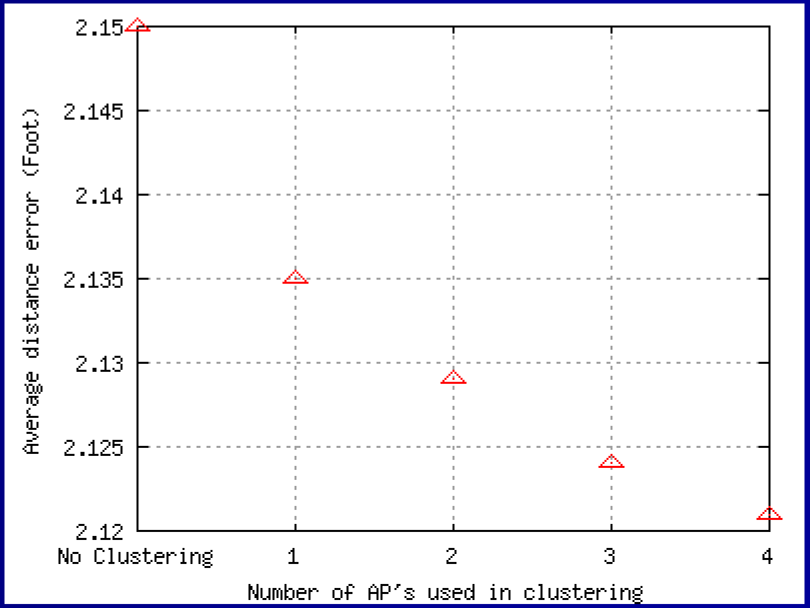
S=[$\underbrace{-45, -60, -70}_{q=3}$, -80, -86]





Locations Clustering:
Results- Explicit Clustering





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

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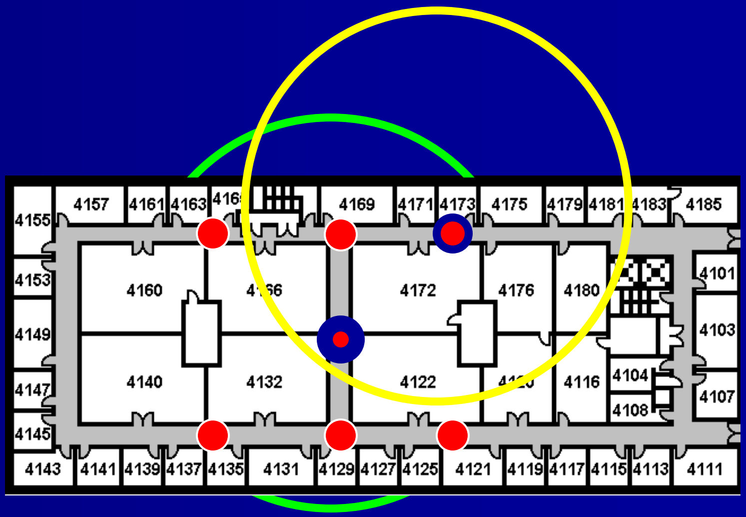
Locations Clustering: Implicit Clustering

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

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

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



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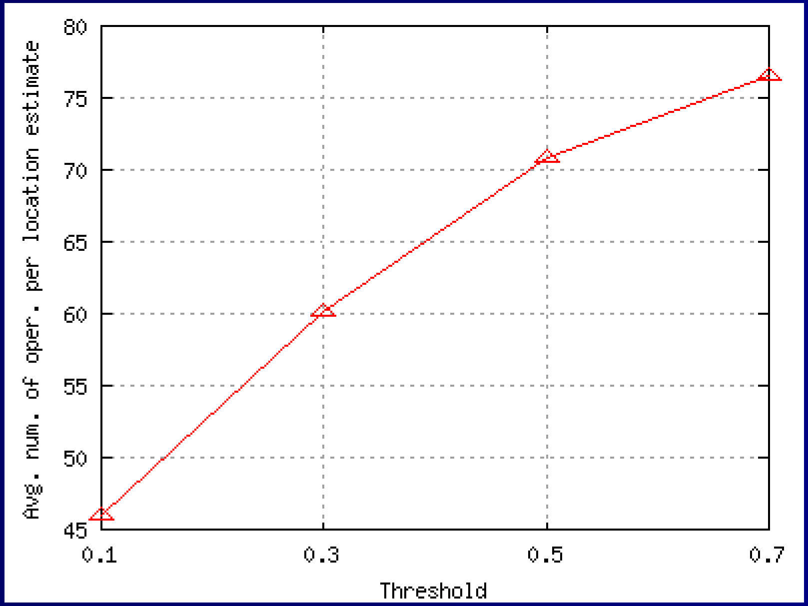
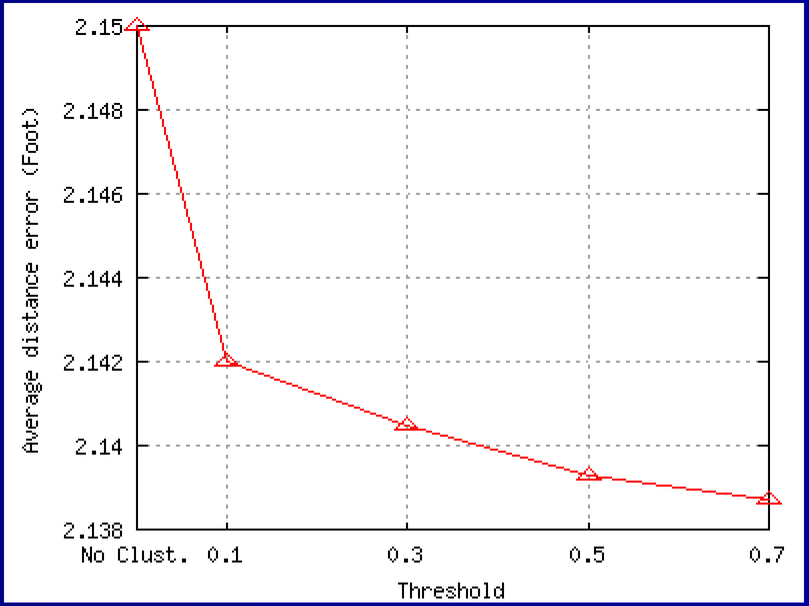
Locations Clustering:

Results- Implicit Clustering





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

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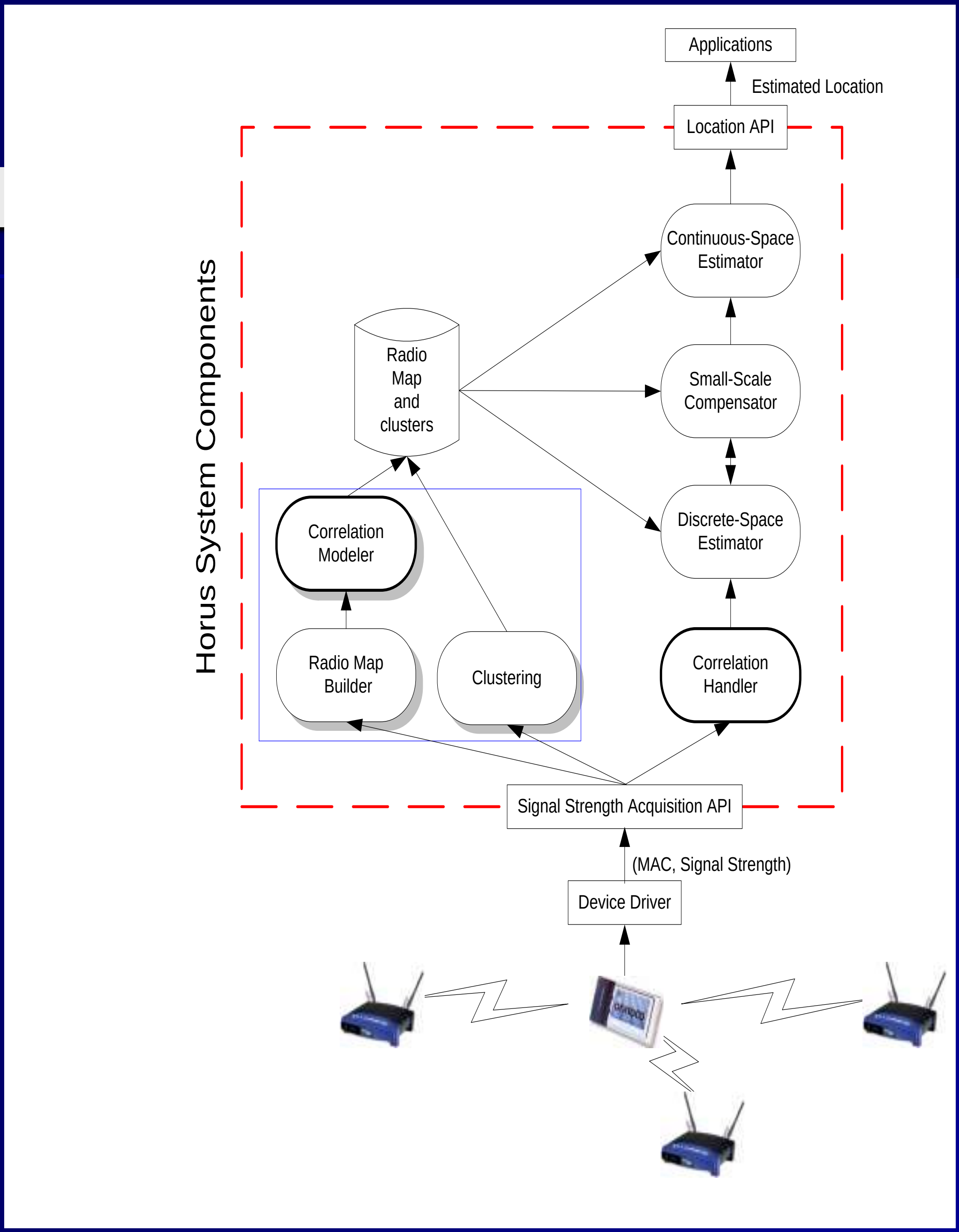

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Roadio-map

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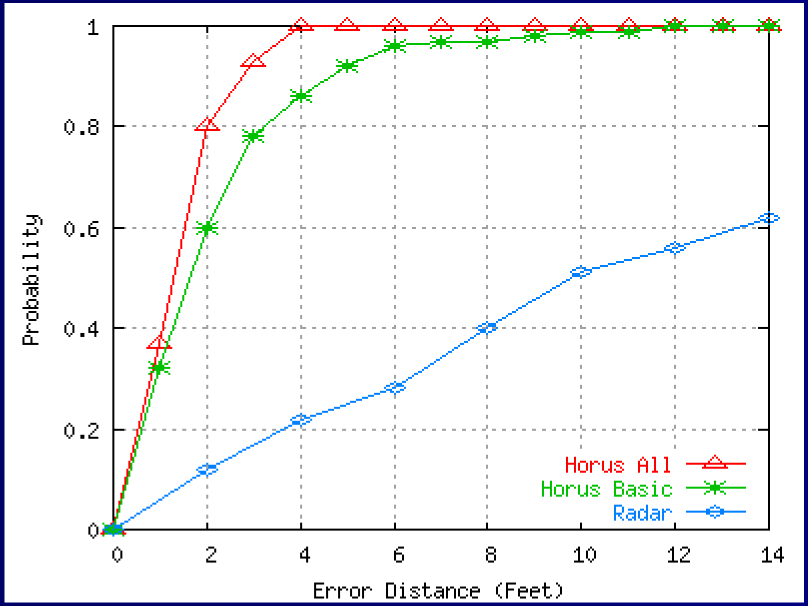
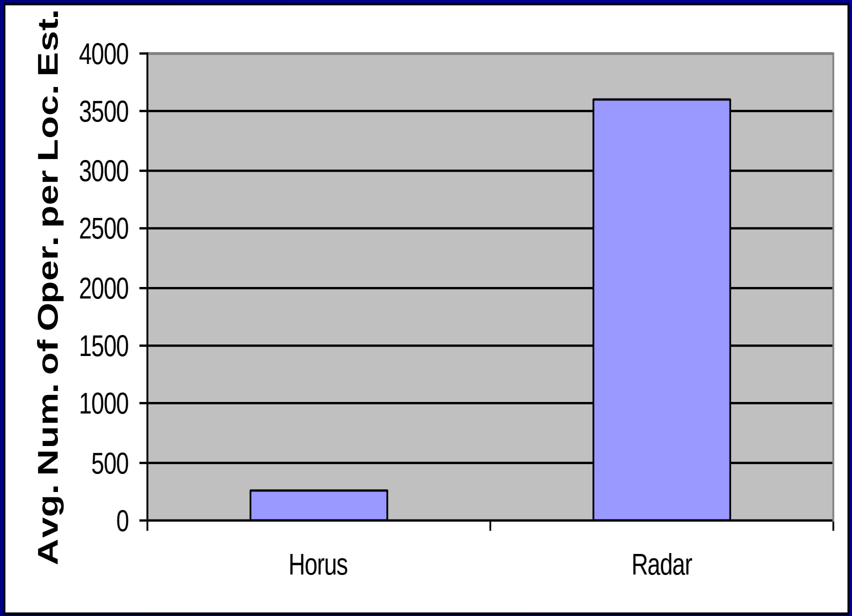
- ✓ Horus components
- ➢ Performance evaluation
- ▪ Conclusions and future work

Horus-Radar Comparison





	Median	Avg	Stdev	Max
Horus (all components)	1.28	1.38	0.95	4
Horus (basic)	1.6	2.16	2.09	18.08
Radar	9.74	13.15	10.71	57.67

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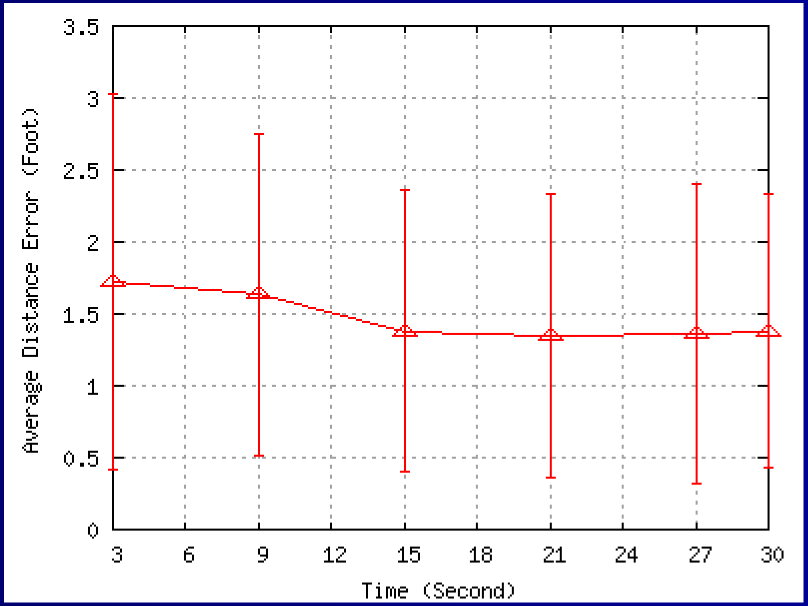
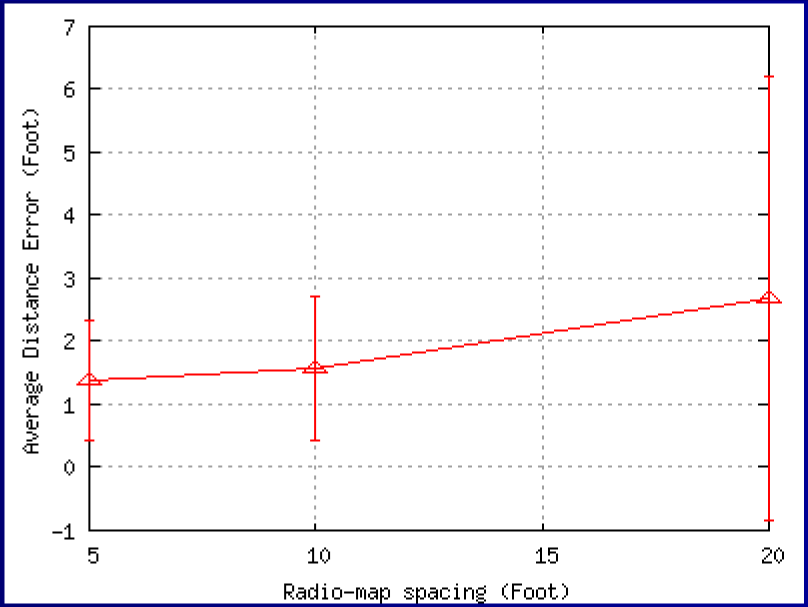
Training Time



- 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

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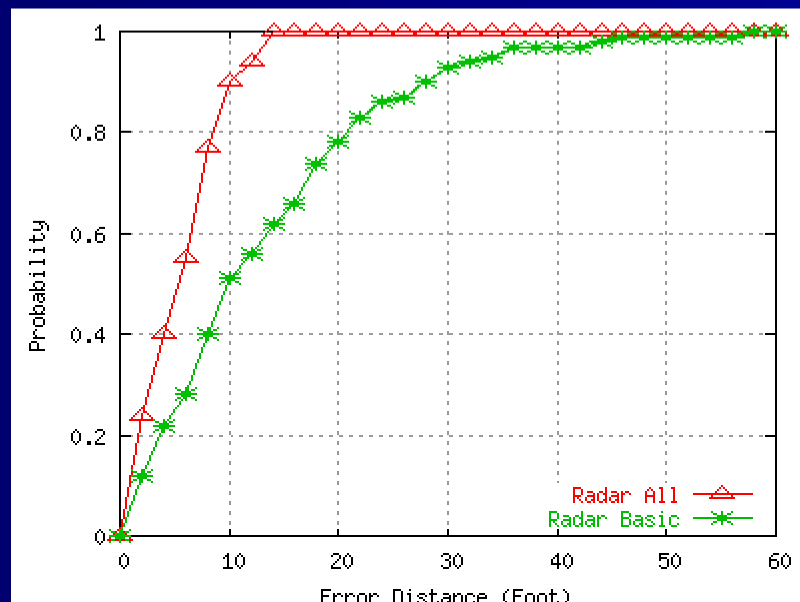
Radar with Horus Techniques



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

Roadio-map

- ✓ Motivation
- ✓ Location Determination technologies
- ✓ Introduction
- ✓ Noisy wireless channel
- ✓ Horus components
- ✓ Performance evaluation
- ➢ Conclusions and future work

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

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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, …

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Future Work

- Using the user history in location estimation and clustering
- Dynamically change the system parameters based on the environment
- Experimenting with other continuous distributions
- Optimal placement of access point to obtain the best accuracy
- Techniques to ensure user privacy

Future Work (Cont'd)

- Different clustering techniques
- Automating the radio-map generation process
- Changing the radio map based on the environment
- Effect of adding/removing access points
- Designing and developing applications and services
- Handling difference between different manufactures

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