Tutorial on Wireless Localization: Existing Approaches, Ongoing Work and Future Challenges

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And many Students!
Rutgers University

Presented at WINLAB, May 2008

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Motivation

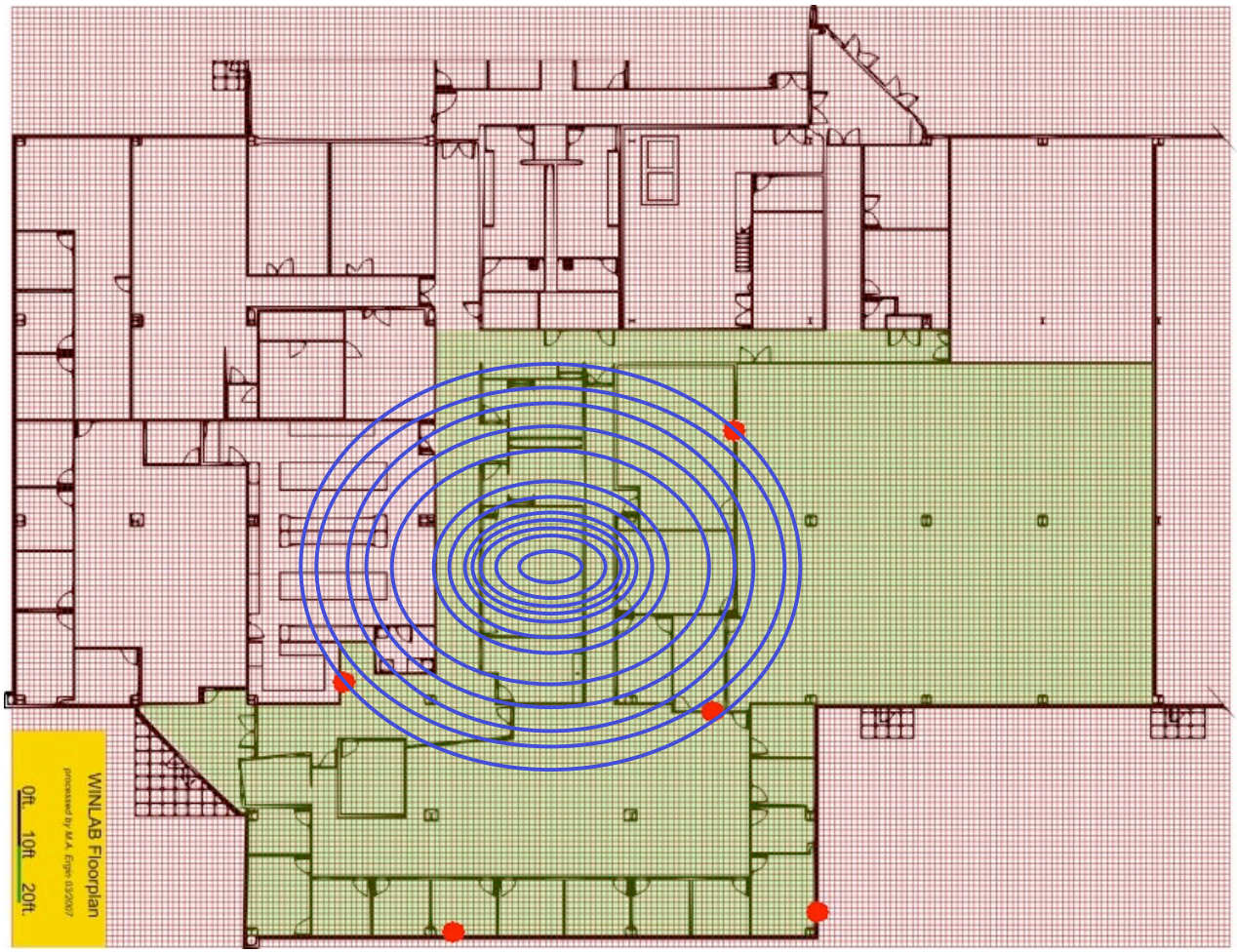
- Technology trends creating cheap wireless communication in every computing device



- Wireless offers localization opportunity in 2D and 3D
- New capability compared to traditional communication networks

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Motivation



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Motivation (cont)

- Real time, physical position of everything
  - $2 active tag plausible (including battery)
  - <$0.25 passive tags
- This talk:
  - Who would use it, and why?
  - History are survey of existing approaches
  - Future Challenges
  - Social implications

A Solved Problem?

- Don't we already know how to do this?
  - Many localization systems already exist
- Yes, they can localize, but ….
  - Missing the big picture
  - Not general

Open problem

- Analogy: Electronic communication
  - 1960's Leased lines (problem solved!) ->
  - 1970's Packet switching ->
  - 1980's internetworking ->
  - 1990's "The Internet":
    - General purpose communication:
    - Communication between any 2 devices on the planet

General purpose localization still open

Opportunity

- General purpose localization analogous to general purpose communication.
  - Work on any wireless device with little/no modification
  - Supports vast range of performance
  - Localize in any environment the device could be in
  - Return device position to the people of concern

Applications

- Scheduling
  - Should we call in more nursing staff this afternoon?
  - Who gets an office today? Tomorrow? Next semester?
- Searching
  - Where is the closest IV pump? Patient's chart?
  - When is the next bus from Busch campus to the train station?
    - How long will it take me to get from CoRE to WINLAB?
- Analysis
  - What did people browse, but not buy?
  - What are the distances to move things in a warehouse?
- Security:
  - Who took the IV pump last?
  - Did the diamond ring move over the last day?

Players and Roles

Area Owners







Network Admins

RUTGERS School of Arts and Sciences Computer Science

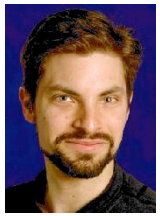
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verizon

Sprint

Device Owners



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Users





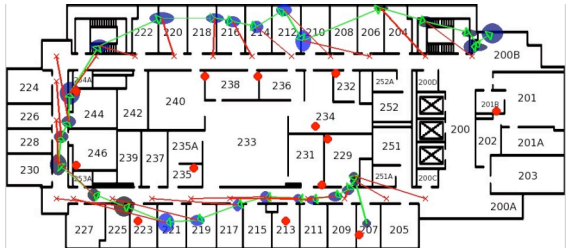
Devices







Applications



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Implied Models

- Device owners
  - own the position information about their devices
  - control who has access to this info.
- Area Owners
  - own the position information about devices in their areas
  - control who has access to this info
- Network operators
  - Not clear. What is relationship to network users?
- Users use applications with position information from these 3 groups

Outline

- Motivation
- Contex: Players and roles
- Localization issues
  - Algorithms, physical layers, metrics
- Algorithms
- Metrics
- Physical Layers
- Open issues and challenges

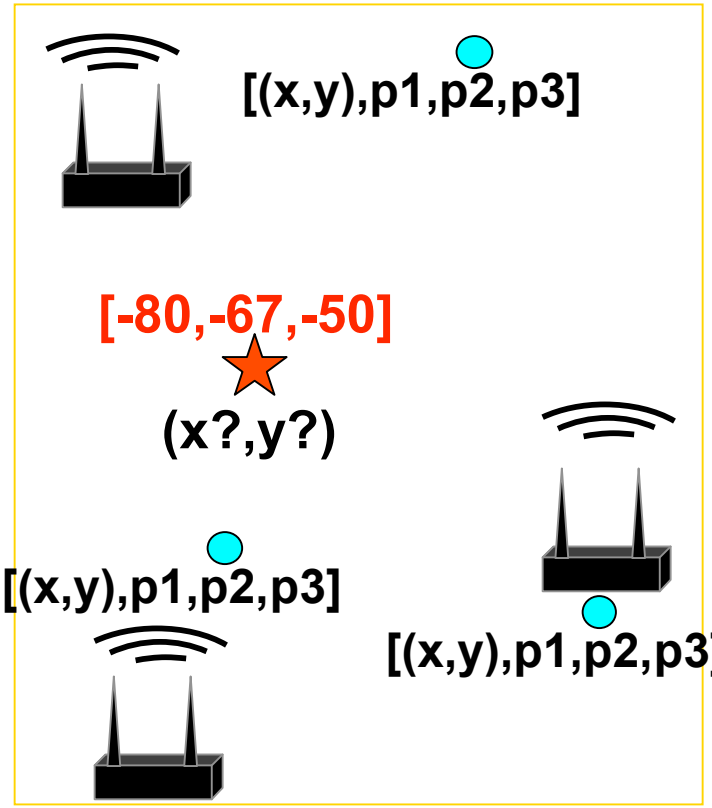
How to Localize?

The key distinctions:

- Algorithmic strategy
  - What observations are needed?
  - Ability to handle uncertainty
    - Precision/accuracy tradeoffs
- Physical layer measurements
  - Observation quality->accuracy, latency,power
  - Limitations on areas, devices

Generic Approach

- Device to localize
- Physical measurements to known locations (landmarks)
  - Fingerprint vectors: $[(x,y),P_1,P_2,P_n]$
  - Set of neighbors + landmarks



Managing Uncertainty

- Physical measurements are unreliable:
  - Measurement error
  - Noise
  - Bias
  - Missing
- Give the user feedback on the uncertainty
- Reporting positions as areas allows precision/accuracy tradeoffs

Performance Metrics

- Accuracy
  - Distance reported vs true location
- Stability
  - Change in reported position vs. motion of device
- Precision
  - Size of returned area

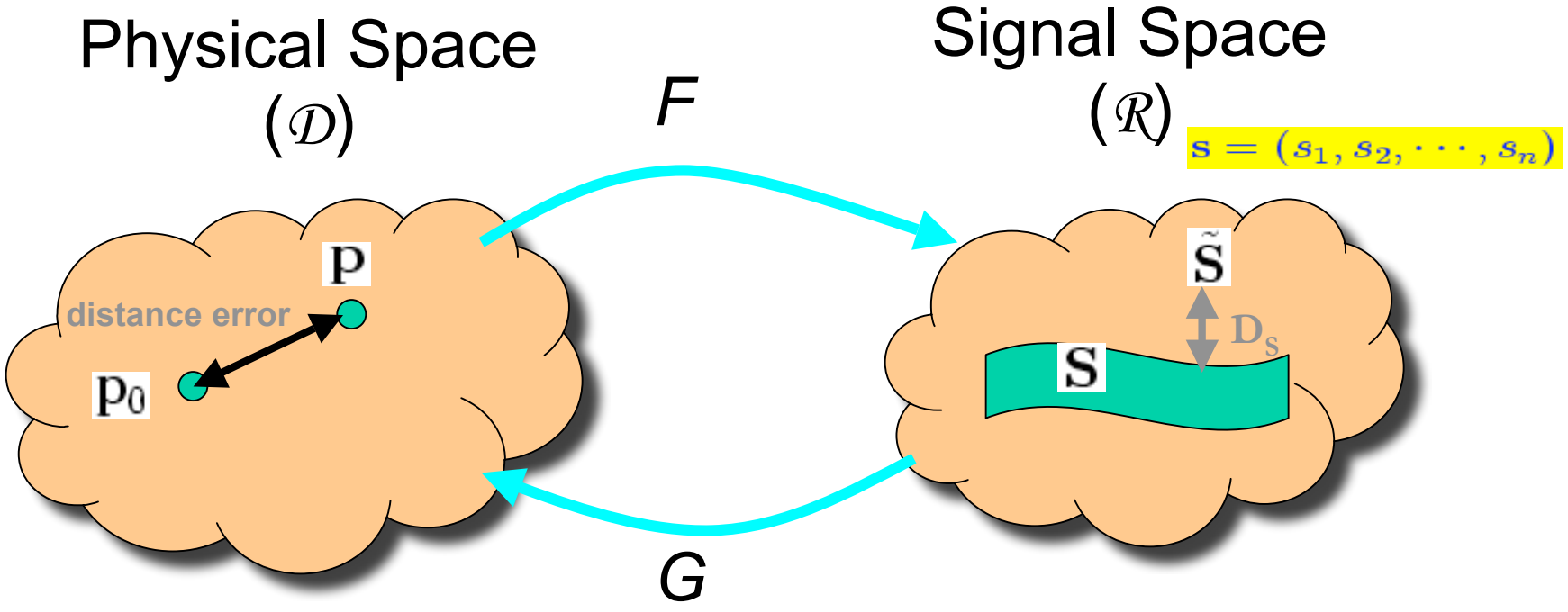
System Metrics

- Latency
  - How long does it take to get a position?
- Scalability
  - # of devices?
- Range
  - What kinds of areas can I cover?
- Generality
  - What devices can be localized?
- Lifetime
  - how long before power runs out?
- Costs
  - hardware, software, installation, maintence,
- Privacy? Security?

Algorithmic Strategies

- Lateration and Angulation
  - Use distances, angles to landmarks to compute positions
- Scene matching
  - The best match on a previously constructed radio map
  - A classifier problem: “best” spot that matches the data
- Aggregate
  - Use constraints on many-course grained measurements.

Generic Paradigm for RSS algorithms



p_0 true location

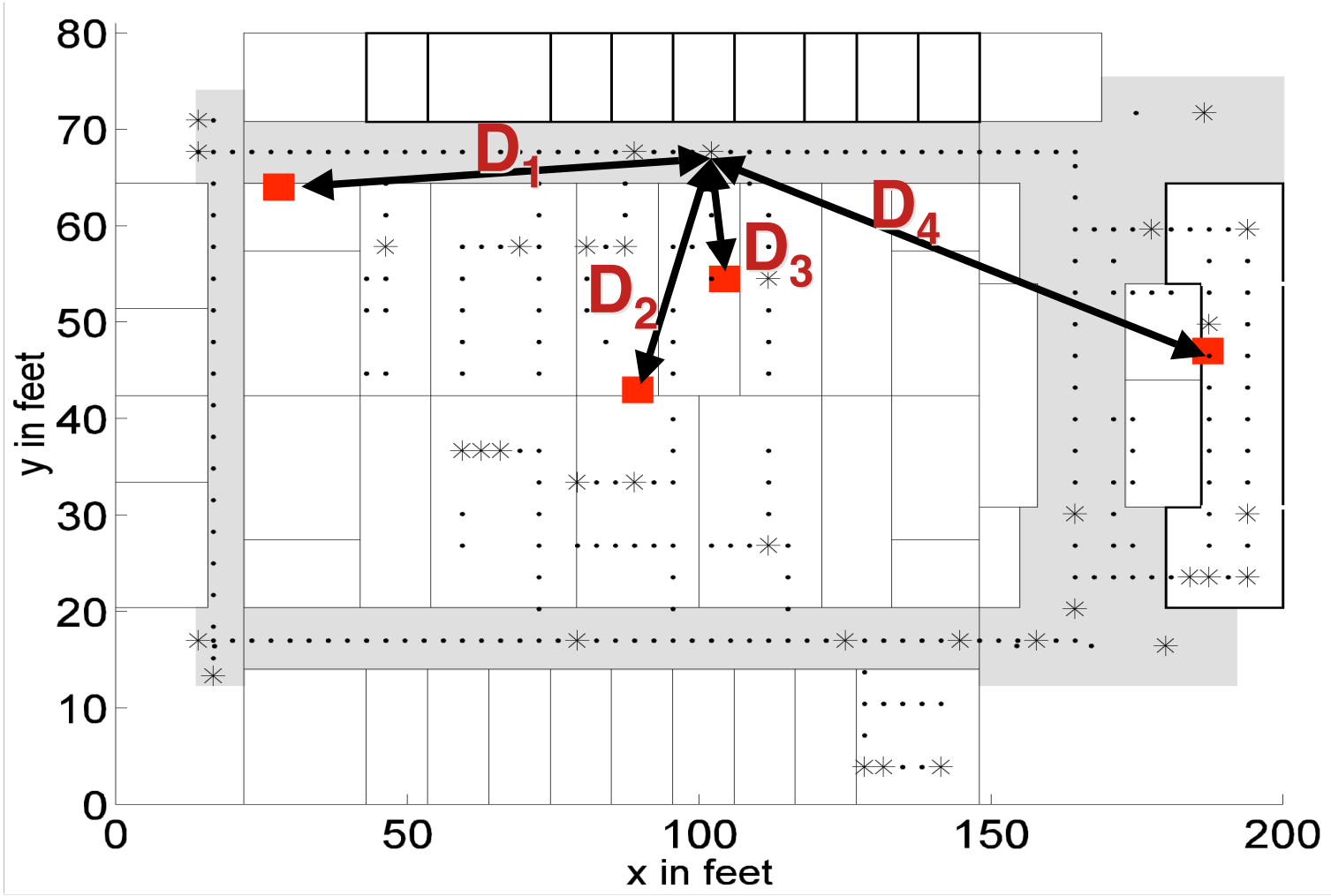
p estimation

Localization:

$$\mathbf{p} = G_{alg}(\mathbf{s})$$

$$\tilde{\mathbf{p}} = G_{alg}(\tilde{\mathbf{s}})$$

Lateration and Angulation



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Scene Matching

- Build a radio map

  [X,Y,RSS_1,RSS_2,RSS_3]

  Training data

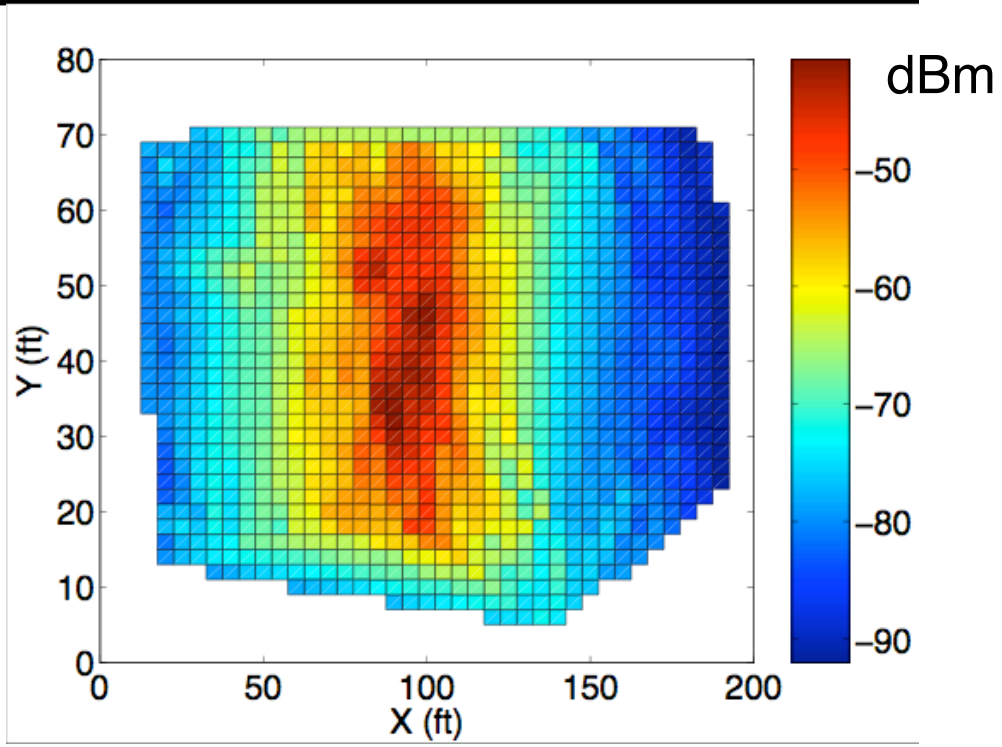
- Classifiers:

  Bayes' rule

  Max. Likelihood

  Machine learning (SVM)

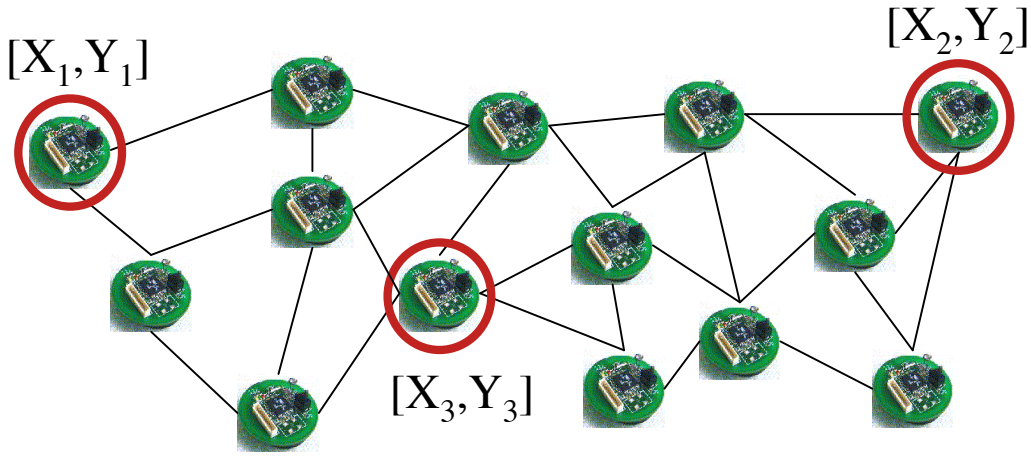
- Slow, error prone
- Have to change when environment changes



Landmark 2

Aggregate Approaches

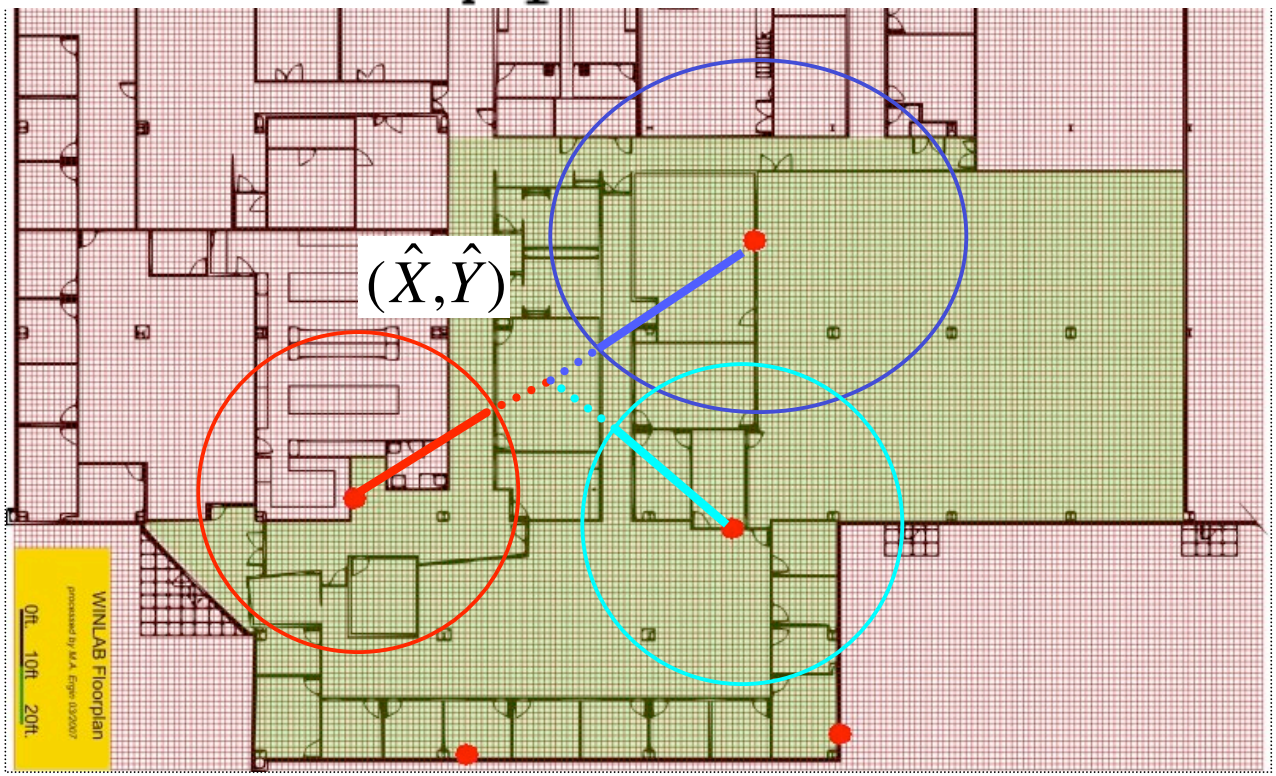
- A field of nodes + Landmarks
- Local neighbor range or connectivity



- Formulations:
  - Nonlinear Optimization problem
  - Multi-Dimensional Scaling
  - Energy minimization, e.g. springs
  - Classifiers

Lateration with Least Squares

$$(\hat{x},\hat{y}) = \arg\min_{x,y} \sum_{i=1}^{n} [\sqrt{(x_i - x)^2 + (y_i - y)^2} - d_i]^2$$

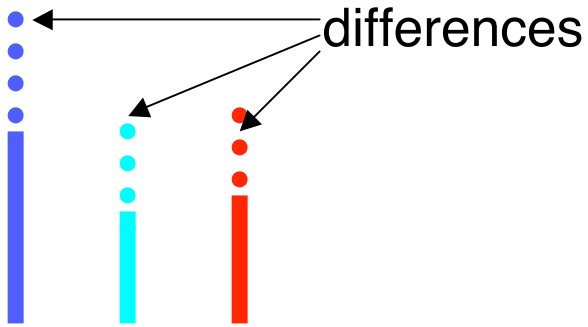


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Least Squares (cont)

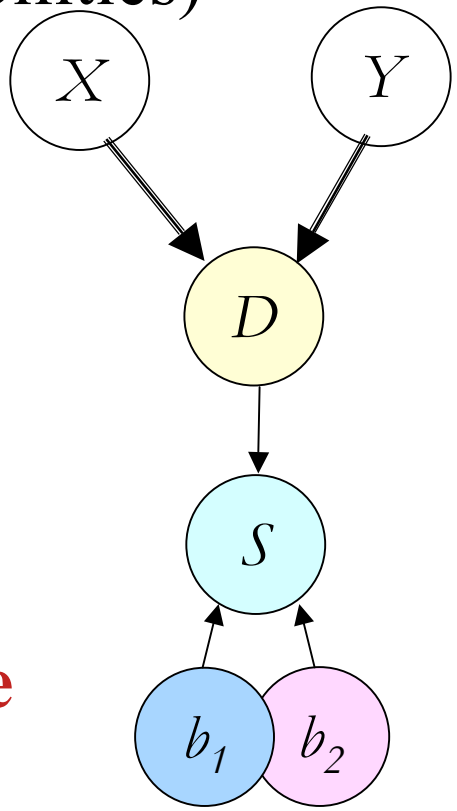
$$(\hat{x},\hat{y}) = \arg\min_{x,y} \sum_{i=1}^{n} [\sqrt{(x_i - x)^2 + (y_i - y)^2} - d_i]^2$$

$(\hat{X},\hat{Y})$ that minimize sum of differences squared



Lateration with Bayesian Graphical Models

Vertices = random variables
Edges = relationships(conditional probabilities)



Example:

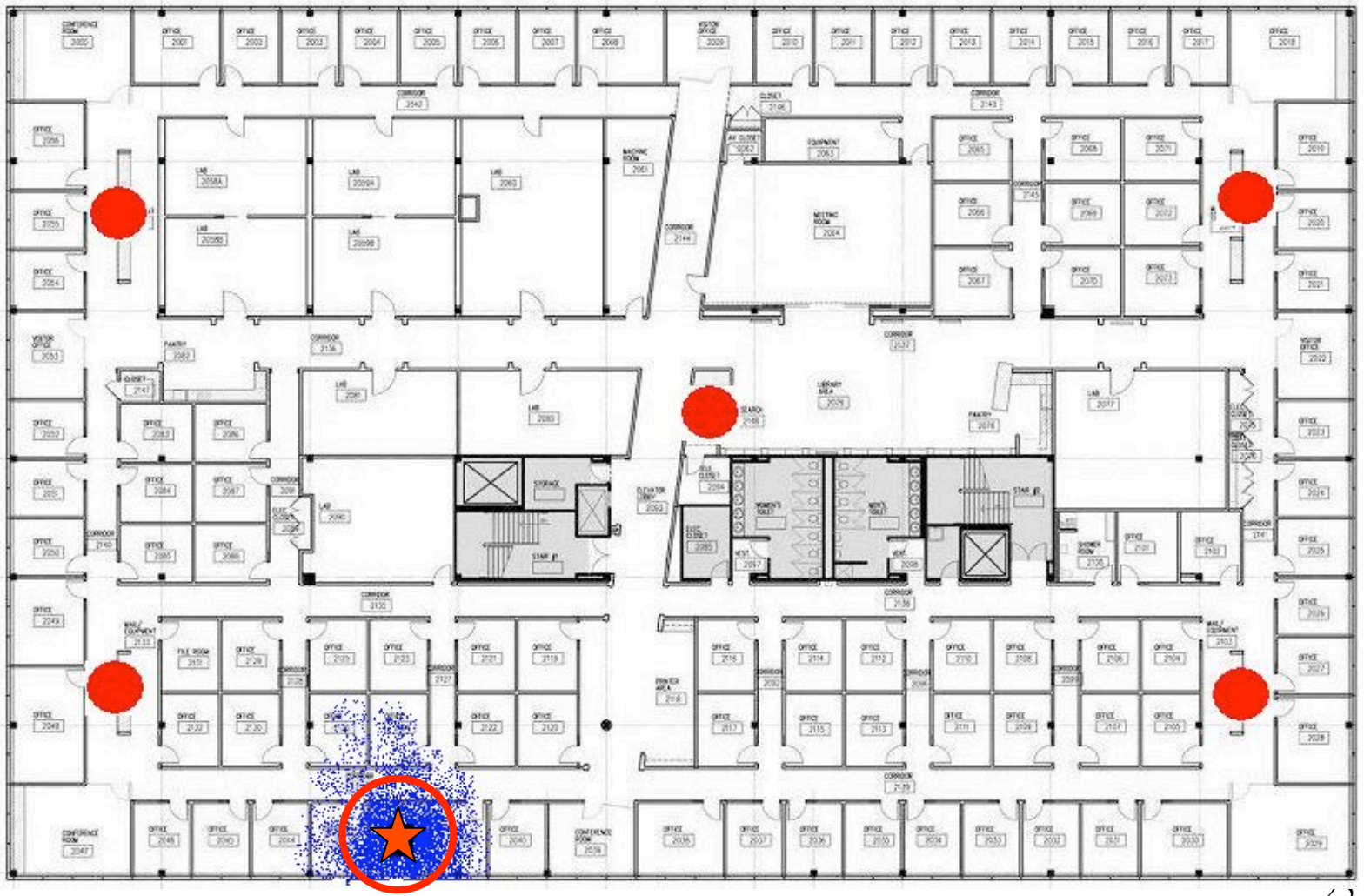
Log-based signal strength propagation

$$S = b_1 + b_2 \log(D)$$

$$D = \sqrt{(x - x_b)^2 + (y - y_b)^2}$$

Can encode arbitrary prior knowledge

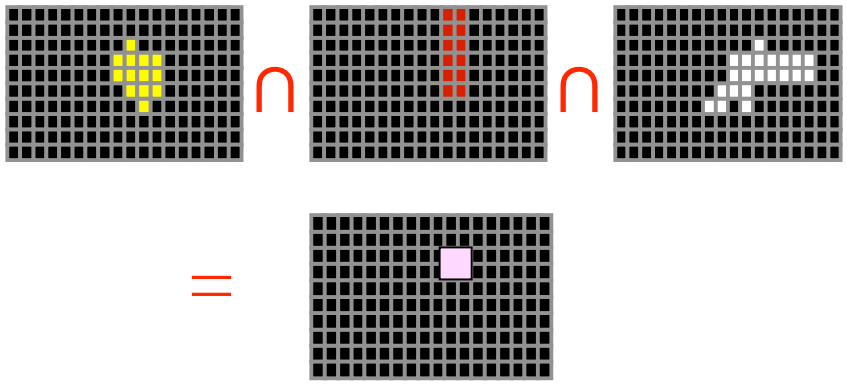
Handling Uncertainty in BN with Monte-Carlo Sampling



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Simple Point Matching (SPM)

- Build a regular grid of tiles, tile ↔ expected fingerprint
- Find ∩ tiles which fall within a "threshold" of RSS for each Landmark



- Eager: start from low threshold (= δ, 2 × δ, …)
- Threshold is picked based on the standard deviation of the received signal
- Approximates Maximum Likelihood Estimation

Aggregate Approach: Multidimensional Scaling

- Given: pairwise data
- Find: A Set of X,Ys that generate the pairwise data
- View as a projection of N(N-1)/2 dimensional space to 2D

Results Overview

- Last 9 years --- many,many varied efforts
  - Most are simulation, or trace-driven simulation
- Aggregate
    - 1/2 1-hop radio range typical.
    - Requires very dense networks (degree 6-8)
- Scene matching
    - 802.11, 802.15.4: Room/2-3m accuracy [Elnahrawy 04]
    - Need lots of training data
- Lateration and Angulation
    - 802.11, 802.15.4: Room/3-4m accuracy
    - Real deployments worse than theoretical models predict (1m)

Outline

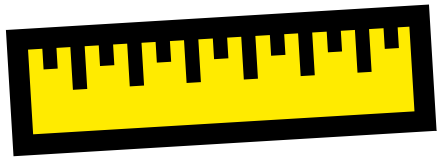
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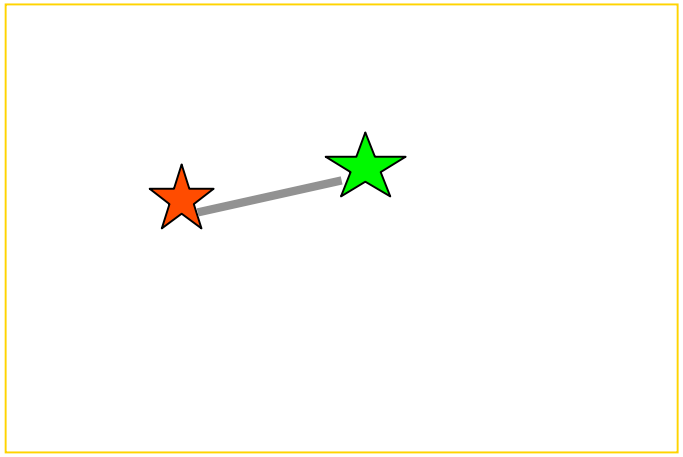
Performance Metrics

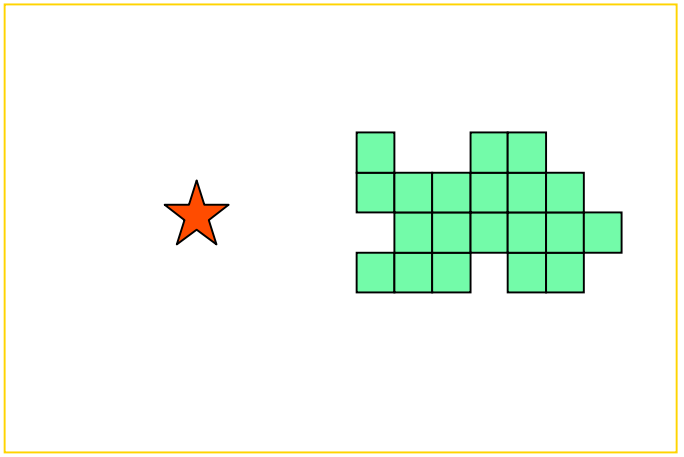
- Algorithmic:
  - Accuracy, Stability, Precision
- System:
  - Range, Generality
- Both:
  - Latency, Scalability
- Costs
  - hardware, software, installation, maintence,
- Privacy?
- Security?

Metrics

- Traditional: **Distance error between returned and true position**
  - Return avg, 95th percentile, or full CDF
  - Does not apply to area-based algorithms!
  - Does not show accuracy-precision tradeoffs!



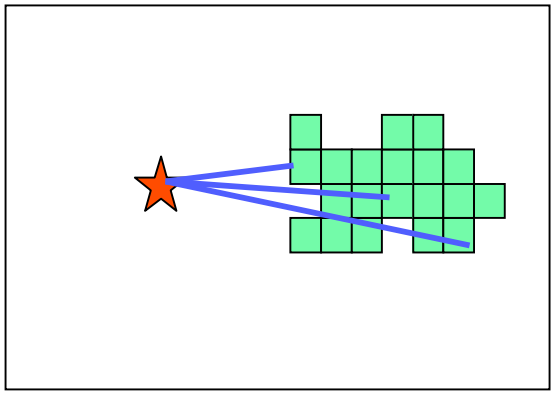




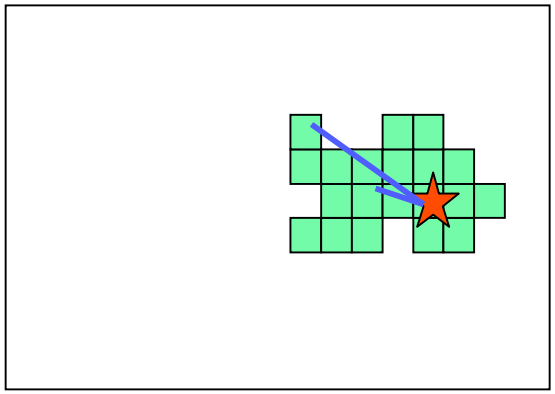


Metrics for Area-based algorithms
Accuracy Vs. Precision

- Tile Accuracy % true tile is returned



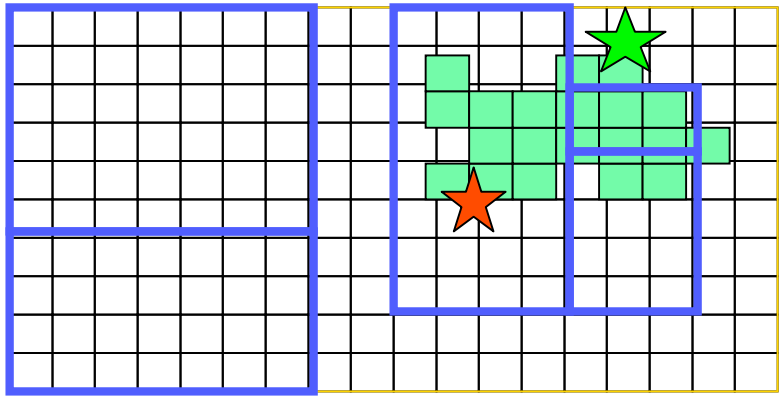
- Distance Accuracy distance between true tile and returned tiles (sort and use percentiles to capture distribution)



- Precision size of returned area (e.g., sq.ft.) or % floor size

Room-Level Metrics

- Applications usually operate at the level of rooms
- Mapping: divide floor into rooms and map tiles
  - (Point ↔ Room): easy
  - (Area ↔ Room): tricky



- Metrics: accuracy-precision
  - Room Accuracy % true room is the returned room
  - Top-n rooms Accuracy % true room is among the returned rooms
  - Room Precision avg number of returned rooms

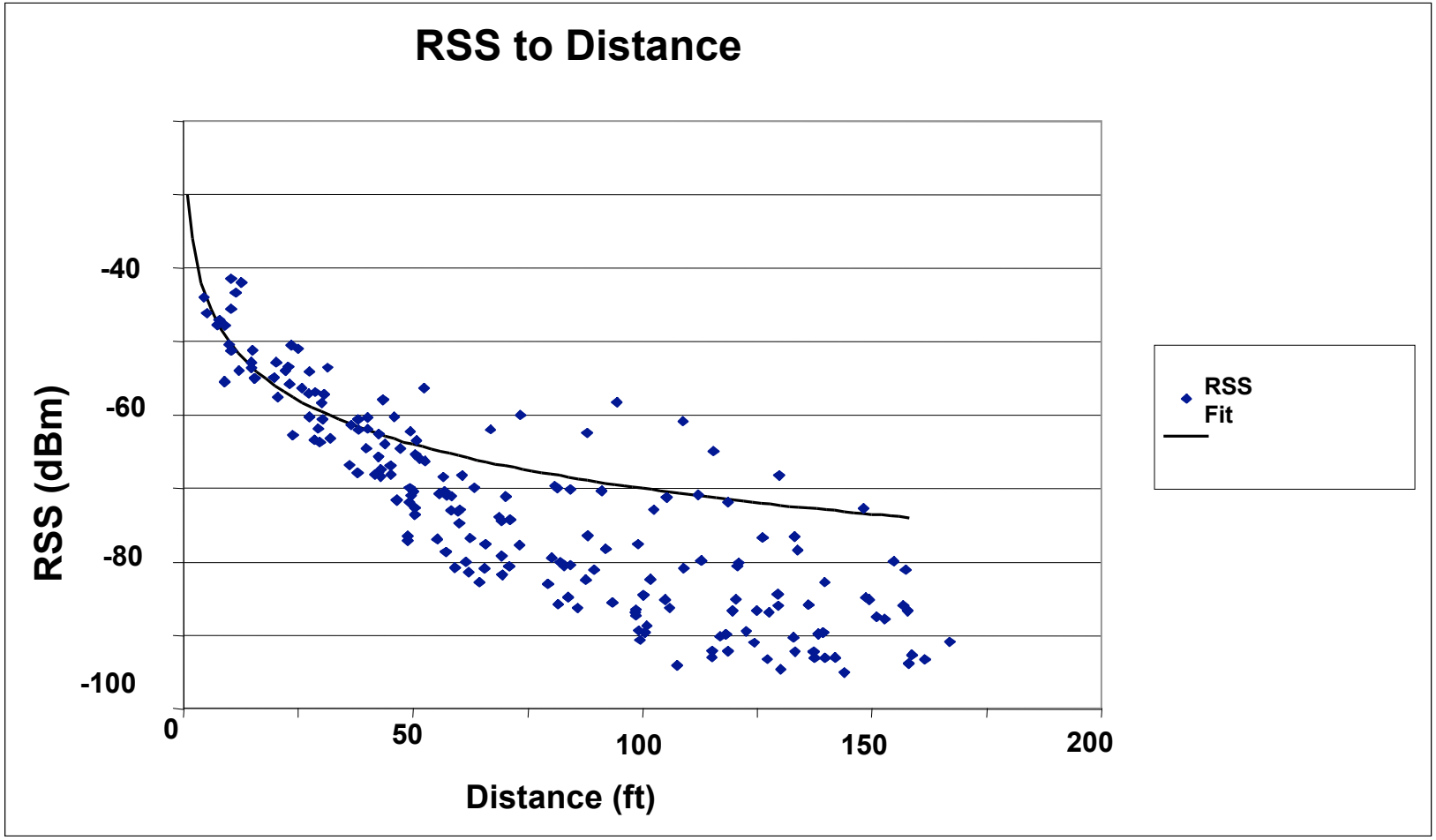
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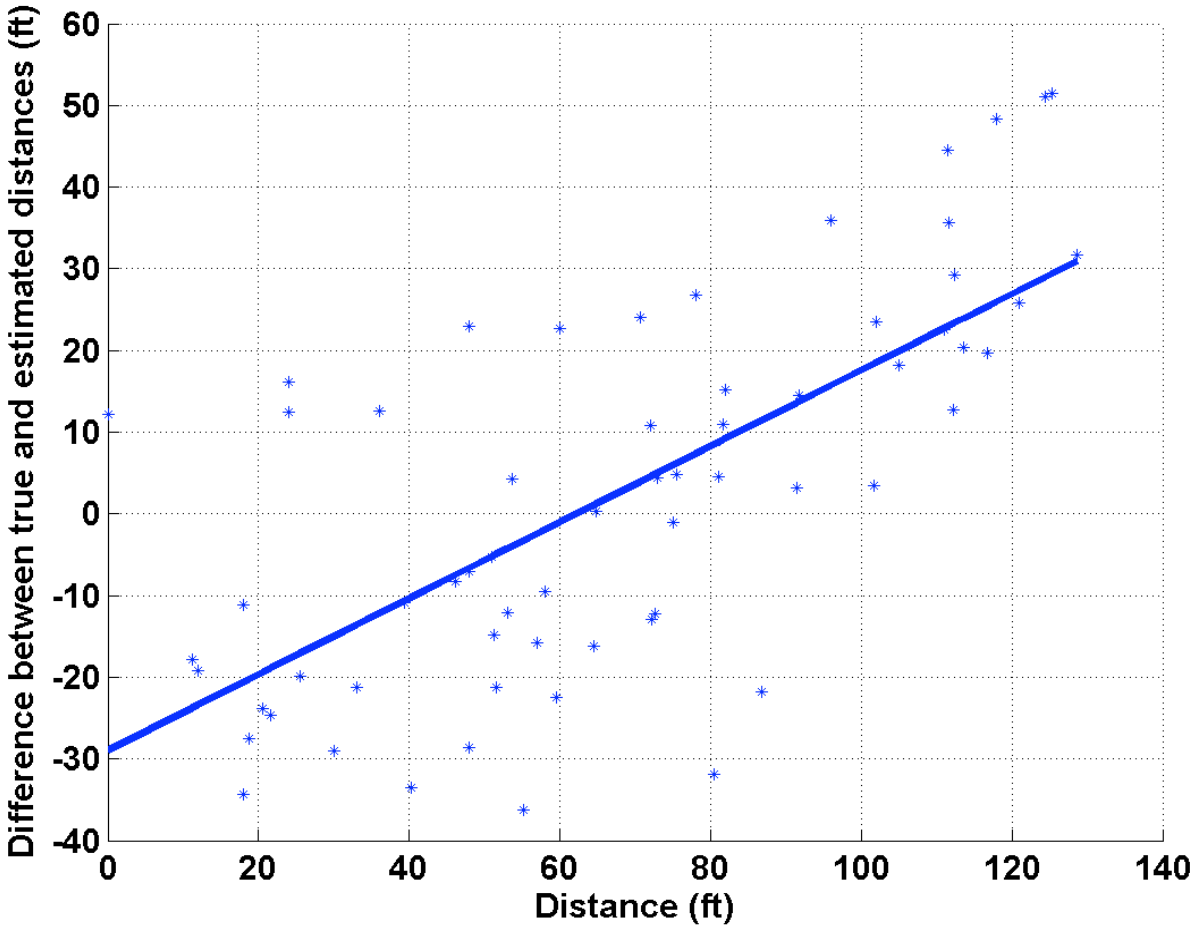
Physical Layers

- Physical proximity
  - 1-hop radio range
- Received Signal Strength (RSS)
- Angle of arrival (AoA)
- Time of Arrival (ToA)
- Time difference (TDoA, ultrasound)
- Phase differences
- Round trip times (RTT)

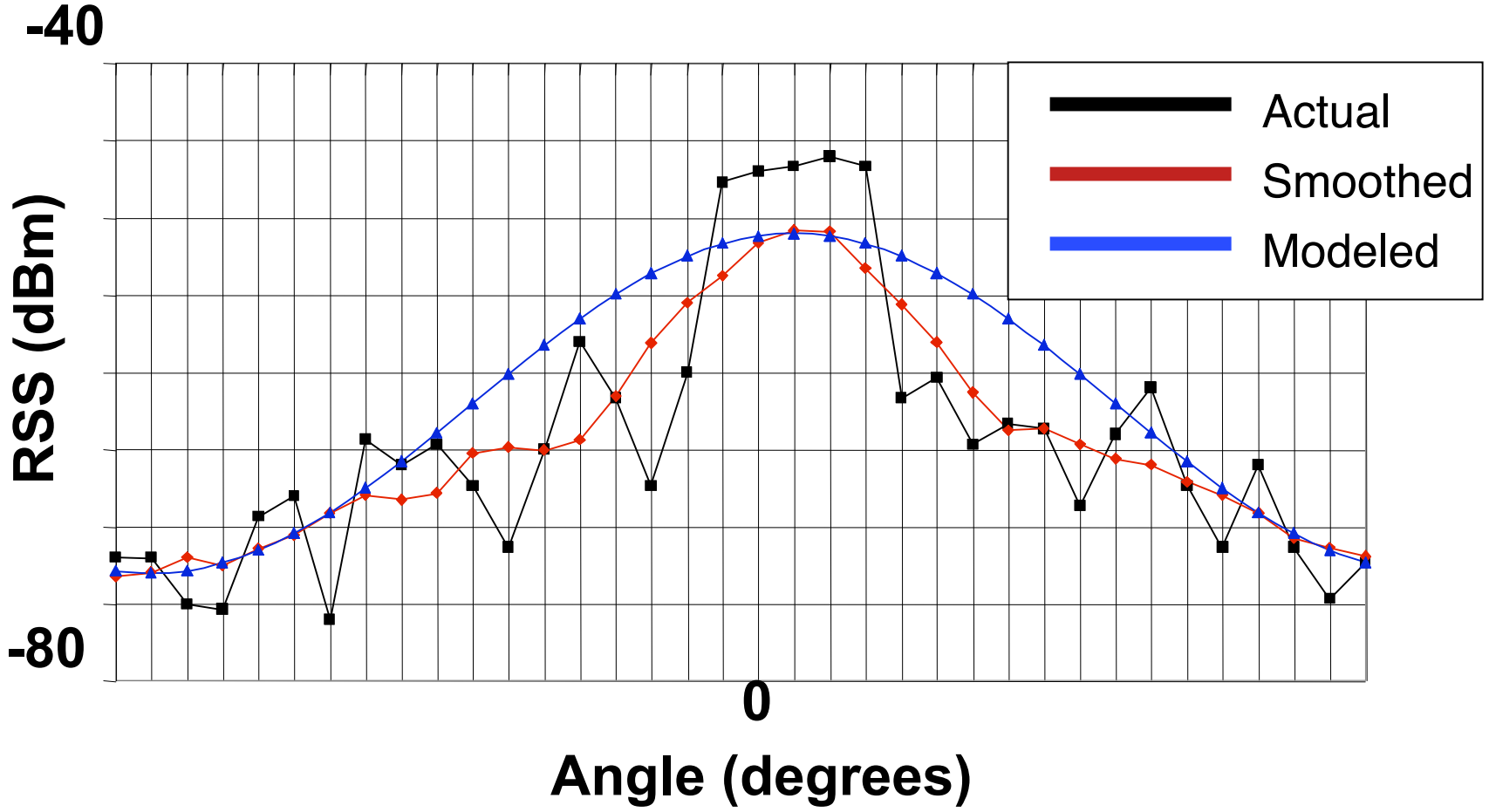
RSS to Distance



Time-of-Arrival to Distance



RSS to Angle (outdoor)



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Future Challenges

- Defining contracts between the players:
  - Who owns the information, how do they control it?
  - Can we build systems to match what's right?
- Leveraging the communication infrastructure
  - What's the limit if we stick to those waveforms?
- Improving the physical layer
  - Cheap way to get better time, angle info?
- Connecting the 'islands'



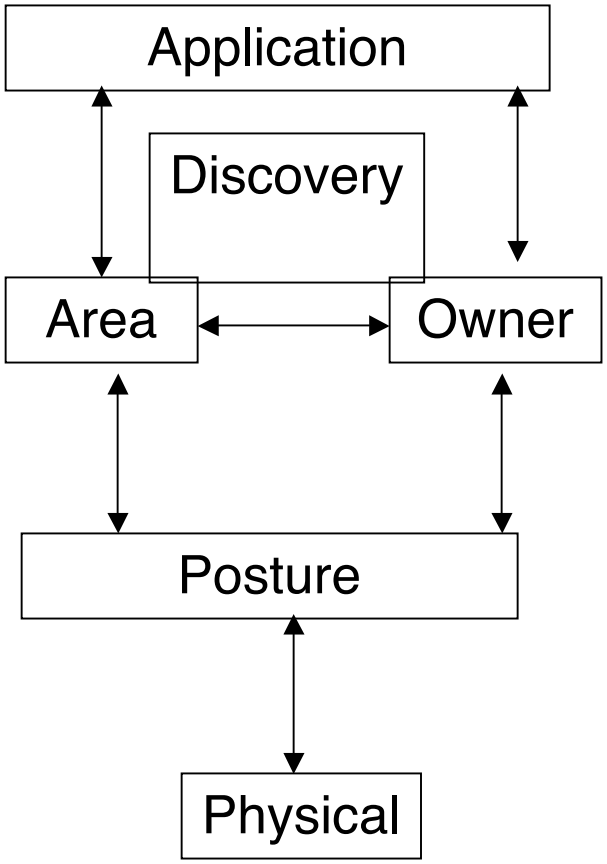
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- Background
- General-purpose Localization Stack
- Examples
- GRAIL overview
- Future Work and Conclusions

Software Components



Stack Overview



Need Standards!

- Purpose and Function
- Protocols (arrows)
- State (boxes)

Application

- Build higher-level applications
  - What is the load in the emergency department?
  - Should we call in more staff for the next shift?
- Collects positions from device owners and area administrators
- Issues:
  - Authentication/Trust
  - Aggregation

Owner

- Questions about devices for a particular owner
  - Person
  - Organization
- All info for a set of devices end up here.
- Separate from the application layer
- Per-Device localization fits this layer
  - Placelab

Area

- Questions about devices inside an area controlled by an administrative domain
  - Areas have “owners” separate from devices.
    - E.g. Computer science dept.
    - Rutgers university
- Gather posture layer info and compute positions
- Current Real Time Location Systems fit this layer
    - GRAIL RTLS (Rutgers)
    - Ubisense
    - Aeroscout

Posture

- Physical observations to position devices.
  - Mean, variance of Rss of observed packets
  - Time difference of arrival
  - Time of arrival
  - Sets of APs/Fingerprints (on a mobile device)
- From Access Point/Landmarks to a central location
- Within a device:
  - about observed landmarks/APs

Physical Layers

- Received Signal Strength (RSS) to Distance
  - Path loss models
- RSS to Angle of Arrival (AoA)
  - Directional antenna models
- Time-of-Flight to distance(ToF)
  - Speed of light (Used in UltraWide band)
- Time Difference of Arrival (TDoA)
  - Ultrasound systems
- Closest base station
  - Infrared tag

Discovery Protocols

- Owners:
  - What applications are available?
  - What areas are my devices in?
- Area administrators:
  - Who's devices are these? Where do I send the info?
- Devices need to:
  - What area am I in?
  - How do I report myself?
  - Access to local signal maps

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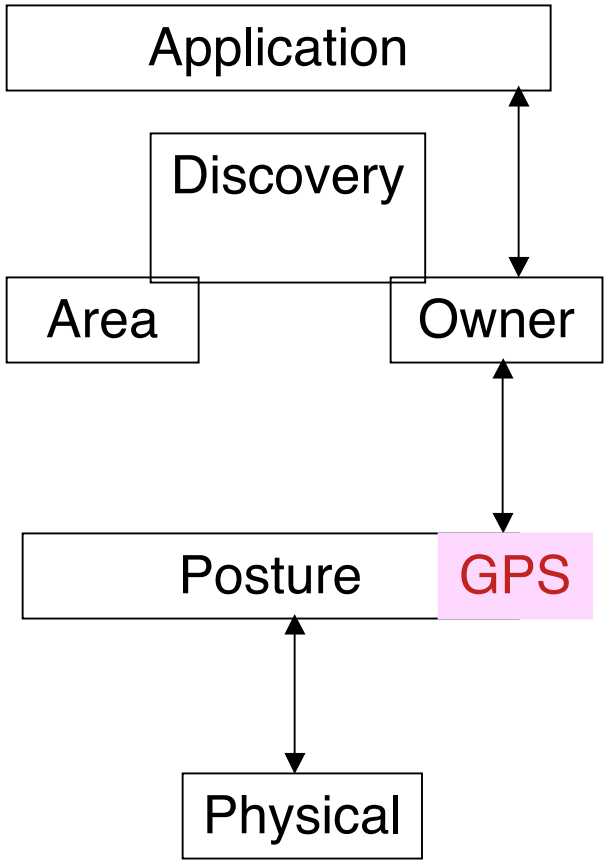
Two extremes

- Powerful device: Mobile phone
  - Complete environment (Linux, JVM)
  - Lots of hardware (WiFi, GPS, 3G, camera)
- Weak device: Active RFID tag
  - Can only send beacons
  - No sensing, storage, no receive
- We have some confidence the localization stack is general purpose if supports both well

Phone Example

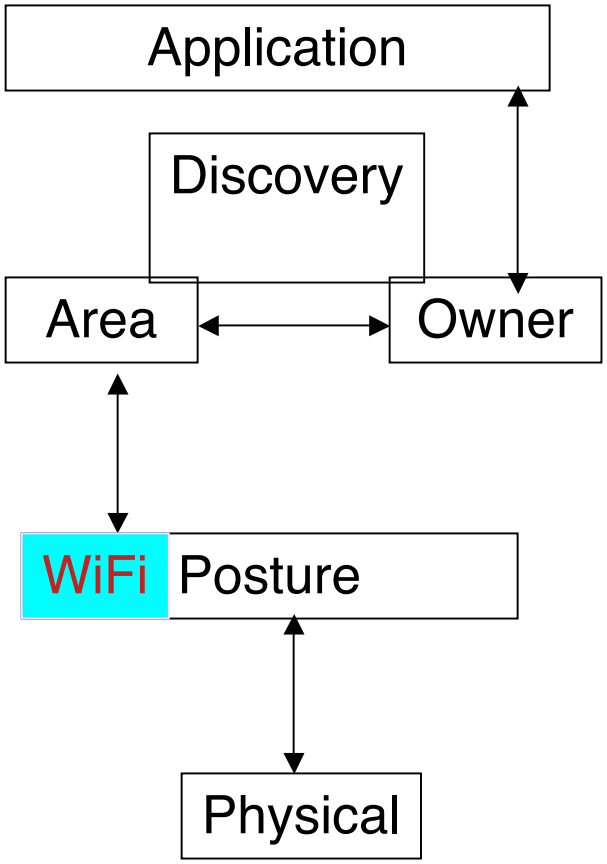
- Where am I application
  - Accessible by: spouse, kids, trusted co-workers
- Scenario: User
  - drives to work
  - works in office
  - goes to a meeting in another building
  - goes to lunch

Drives to work



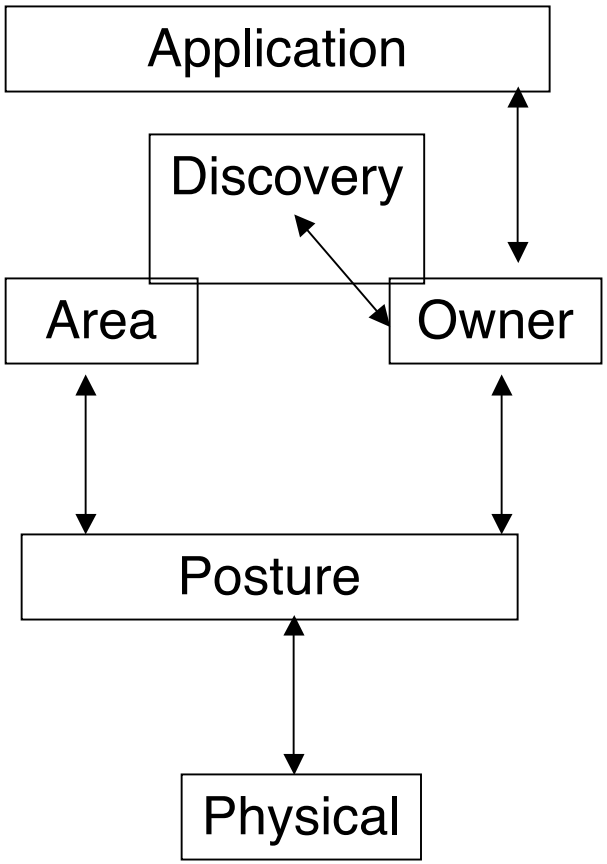
- Phone uses GPS/3G
- Phone runs posture protocol with GPS
- Sends into to owner server over 3G

Works in Office



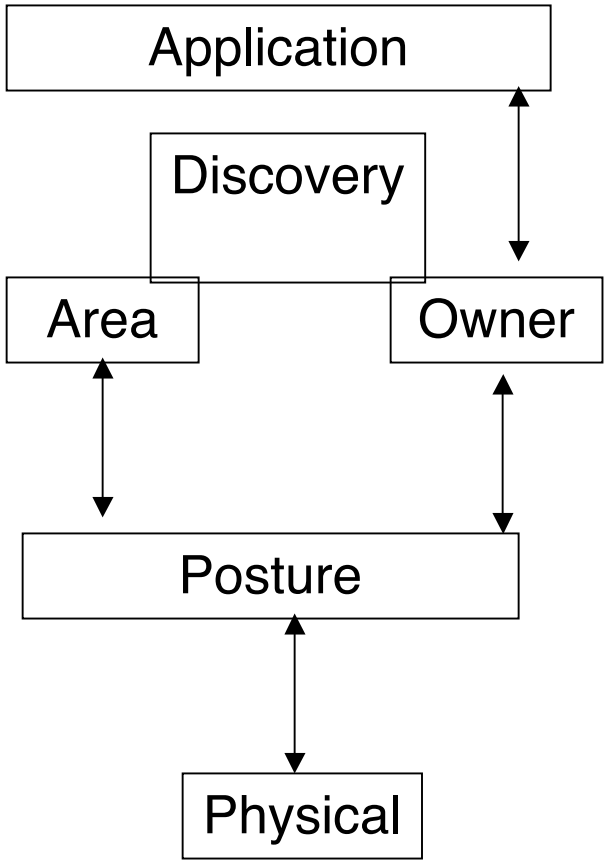
- Area controlled by phone's organization
- Phone Connects to network
- Landmarks communicate Phone's RSSI to dept. location server
- Dept. Location server reports phone's position to owner's server

Meeting in another building



- Area controlled by outside department
- Phone discovery over local WLAN
- Phone Area server requests a WiFi signal map
- Reports to owners server via local WLAN

Goes to Lunch



- Open WiFi in a Café
- No response to WLAN discovery
- Run a local area server on the Phone
- Wide Area Discovery with known server
- Uses closest basestation to report position based on public DB of WiFi AP locations

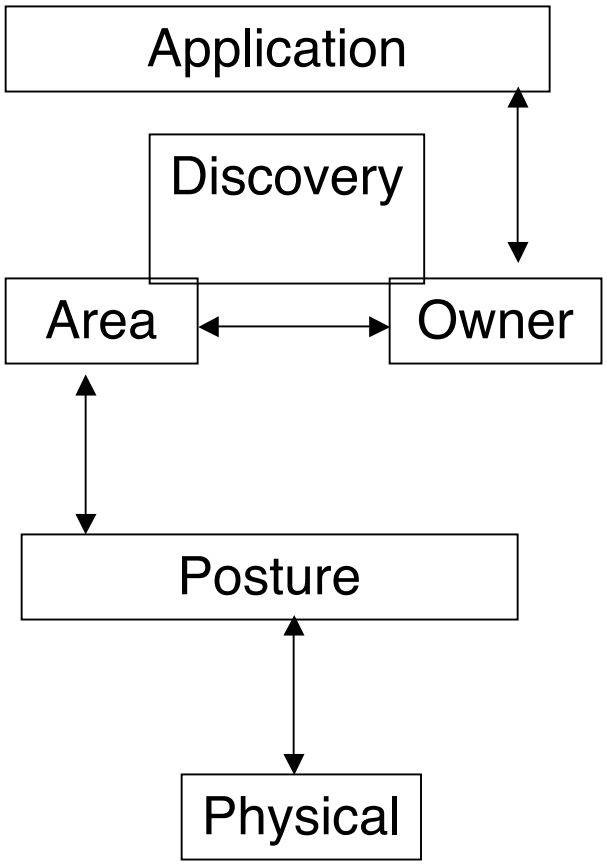
RFID tag example

- Tagged a notebook
- User brings notebook to work
- Takes notebook on trip
  - Stays in a hotel
  - Returns home
- Forgets notebook in trunk of car at home

RFID example

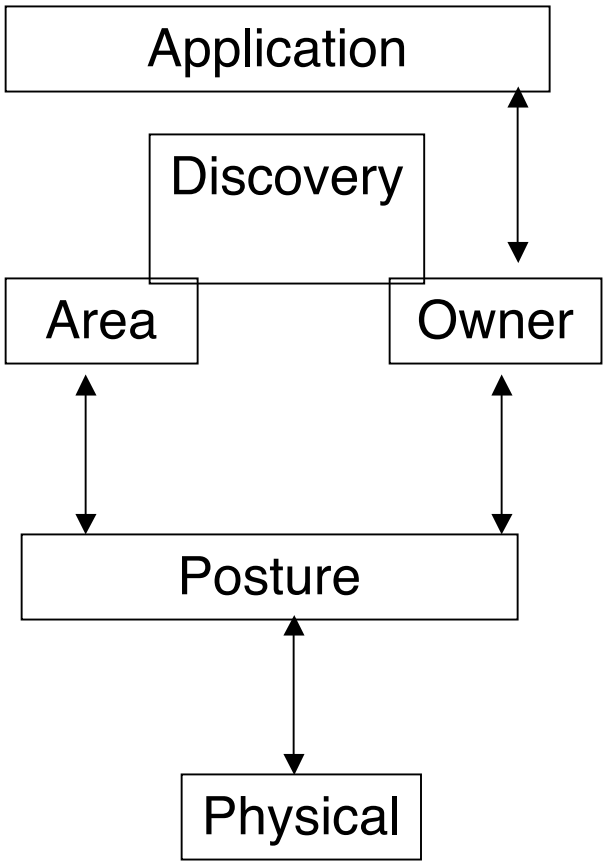
- Key idea:
  - RFID readers run both posture and area protocols
- 1 reader in the car
- 1 reader at work
- 1 reader in laptop

Brings Notebook to Work



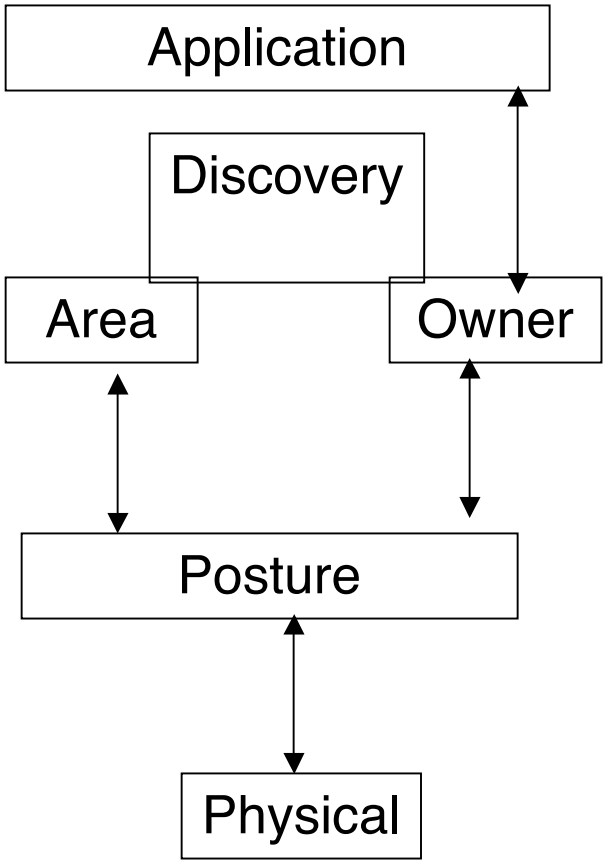
- Readers on desk, bookshelf, laptop hear tag beacons
- Location server computes position of the tag and laptop
- Report to owner's server

Takes notebook to hotel



- Laptop computes position based on public WiFi list
- Laptop becomes an area server
- RFID reader on laptop gets position from laptop area server
- sends closest basestation location to owner's server

Leaves notebook in car



Area server in car gets position via GPS

- RFID reader in car gets position from car's area server
- Reports tags' position to user's owner server

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GRAIL

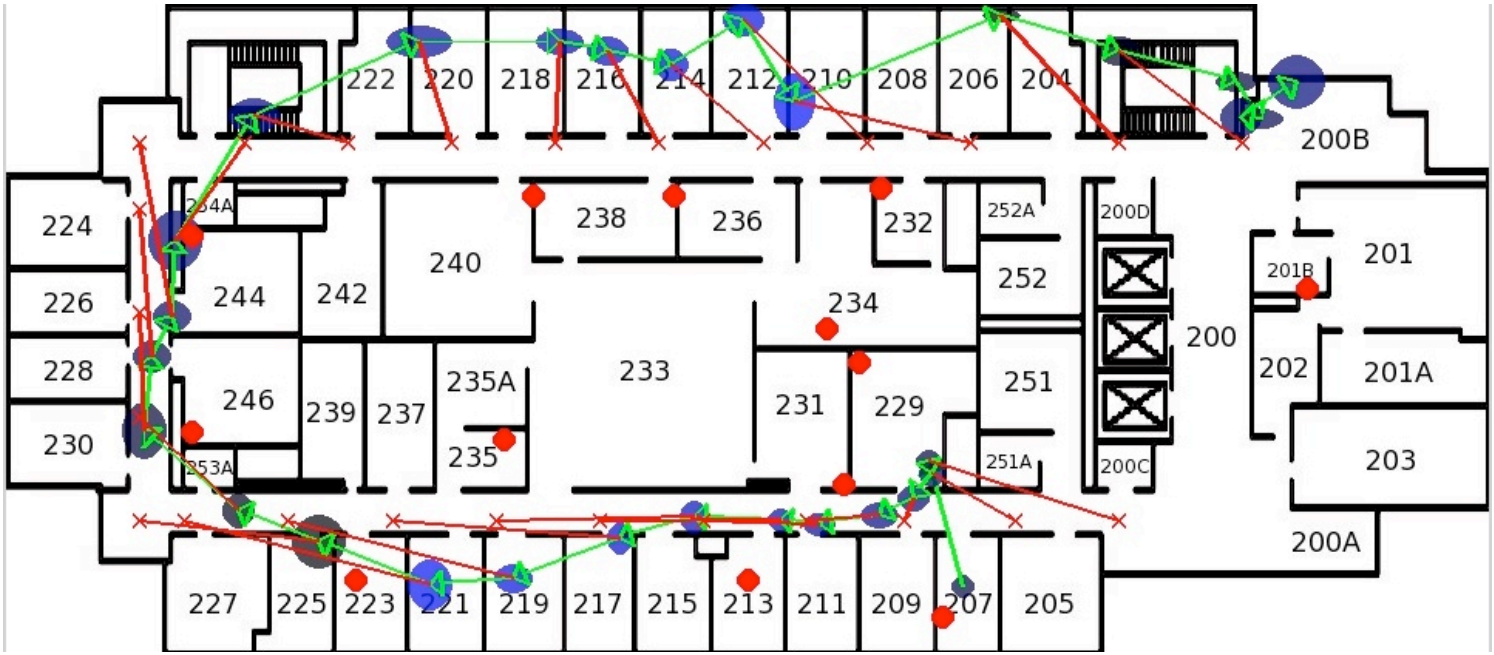
- Area System for localization
  - Demo at WINLAB Tuesday

  – General Purpose
  – Real Time
  – Adaptable
  – Indoor
  – Localization

Packet-level, Centralized Approach

- Deploy **Landmarks**
  - Monitor **packet traffic** at known positions
  - Observe packet radio properties
    - Received Signal Strength (RSS)
    - Angle of Arrival (AoA)
    - Time of Arrival (ToA)
    - Phase Differential (PD)
- **Server** collects per-packet/bit properties
  - Saves packet information over time
- **Solvers** compute positions at time T
  - Can use multiple algorithms
- **Clients** contact server for positioning information

Example tracking EeePC



Estimated Position

Groundtruth

Landmark

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Future Work

- Rebuild and deploy system
  - Gain experience running over weeks, months
- Continue to improve landmarks
  - High frequency, bit-level timestamps
- Scalability
  - Parallelize sampling algorithms
- Security
  - Attack detection
  - Algorithmic agreement
- Social issues?

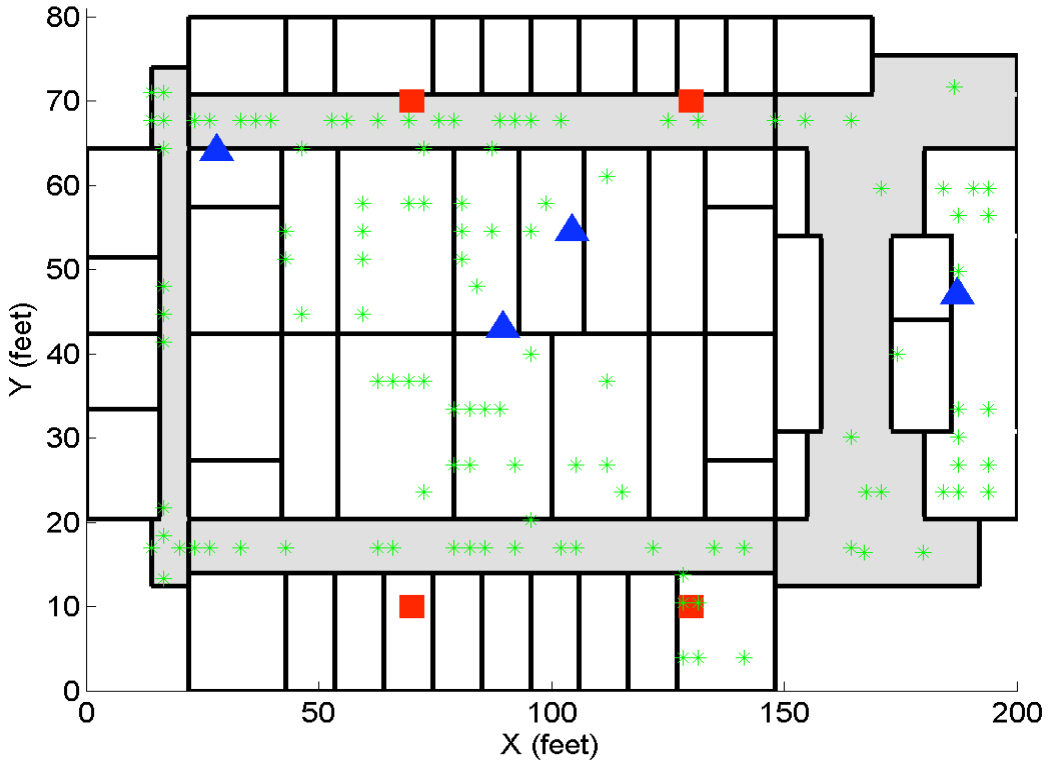
Conclusions

- Time to defocus from algorithmic work
- Localization of all Wireless will happen
  - Expect variety of deployed systems
  - Demonstration of cost/performance tradeoffs
  - Islands first, then interconnect the islands
- Technical form, social issues not understood

Backup slides

Communication vs. Localization

- Resource use for Localization vs. Comm.?
  - Ideal landmark positions not the same as for comm. coverage [Chen 2006]



Incorporating Angle-of-Arrival

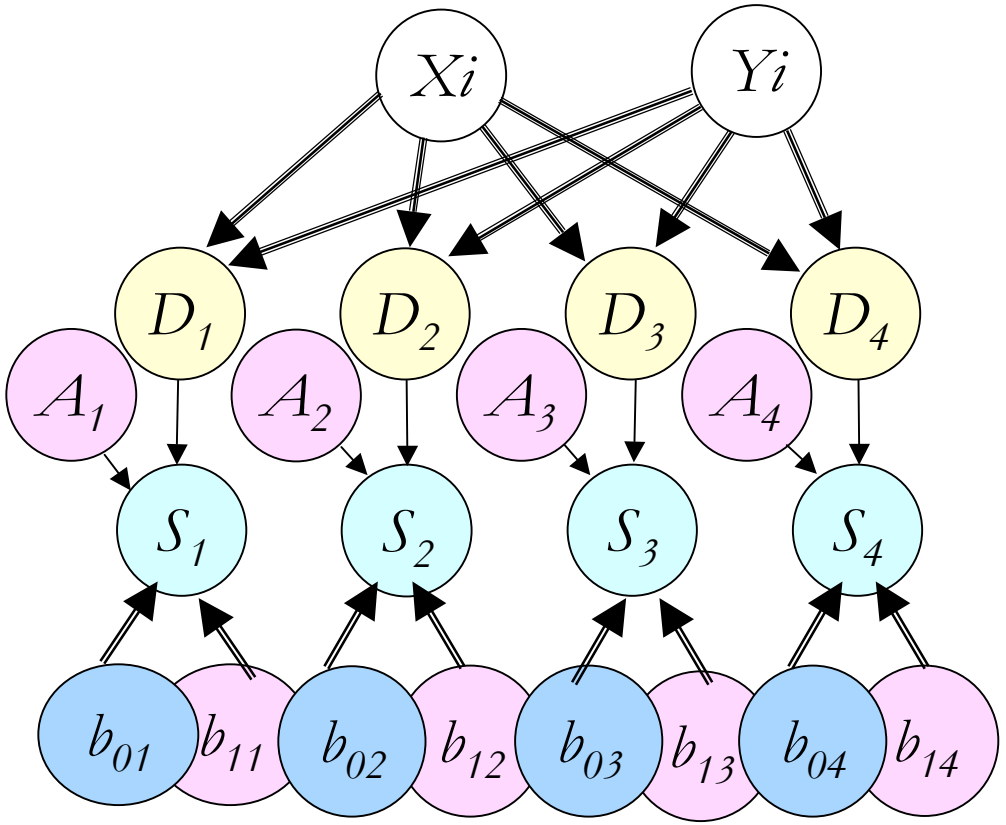
Position

Distance

Angle

RSS

Propagation Constants

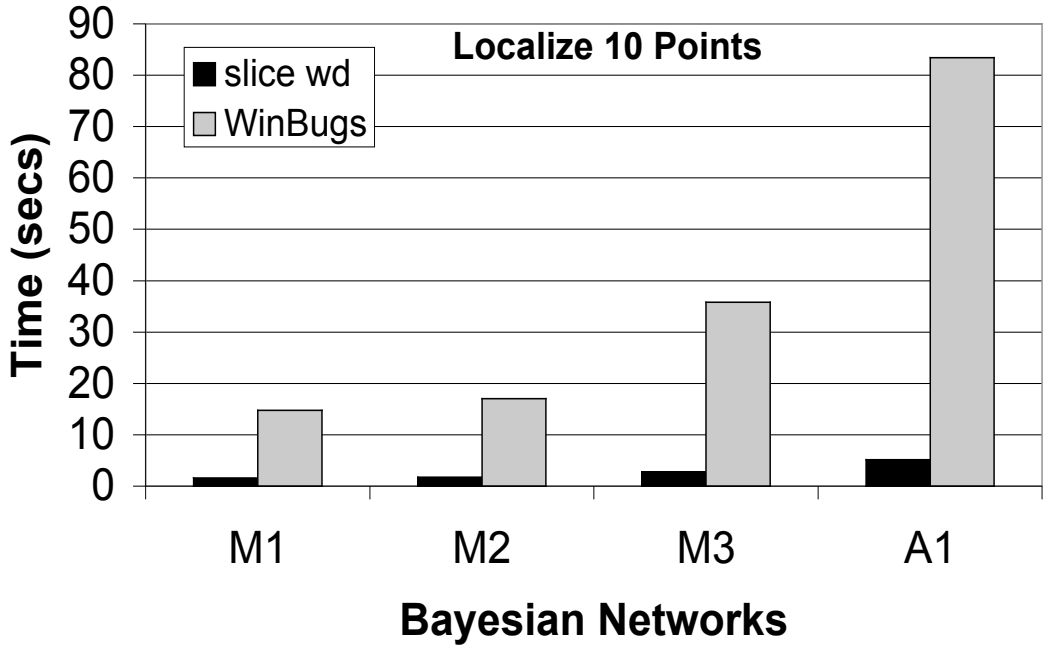


Minus: no closed form solution for values of nodes

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Scalability

- Can scale to 10's of unknowns in a few seconds
- Can we do 1000s?



References

- Today's talks:
  - Kosta: Rapid sampling of Bayesian Networks
  - Yingying: Landmark placement

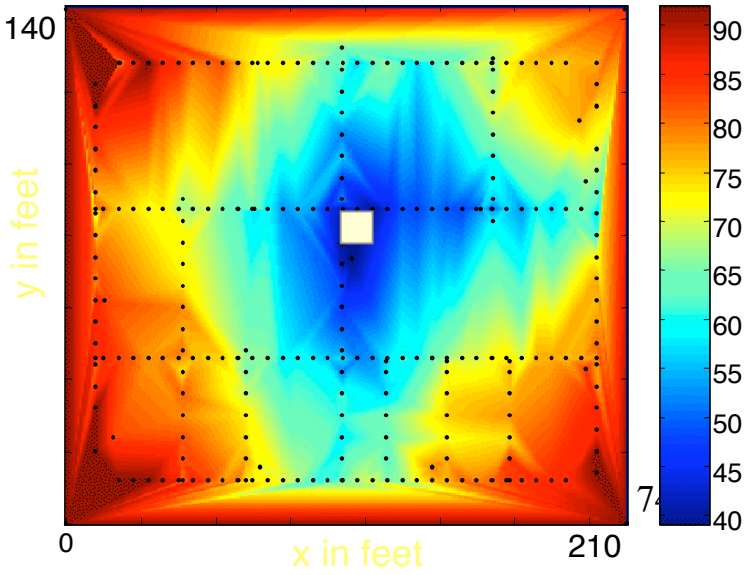
- E. Elnahrawy ,X. Li ,R. P. Martin, The Limits of Localization Using Signal Strength: A Comparative Study In Proceedings of the IEEE Conference on Sensor and Ad Hoc Communication Networks, SECON 2004

- D. Madigan , E. Elnahrawy ,R. P. Martin ,W. H. Ju ,P. Krishnan ,A. S. Krishnakumar, Bayesian Indoor Positioning Systems , INFOCOM 2005, March 2004

- Y. Chen, W. Trappe, R. P. Martin, The Robustness of Localization Algorithms to Signal Strength Attacks: A Comparative Study, DCOSS 2006

Measurement At Each Tile Is Expensive!

- Interpolated Map Grid: (Surface Fitting)
- Goal: Extends original training data to cover the entire floor by deriving an expected fingerprint in each tile
- Triangle-based linear interpolation using "Delaunay Triangulation"
- Advantages:
  - Simple, fast, and efficient
  - Insensitive to the tile size



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Scene Matching: RADAR