Emerging Wireless Device Localization Systems

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RUTGERS School of Arts and Sciences Computer Science

WINLAB WIRELESS INFORMATION NETWORK LABORATORY

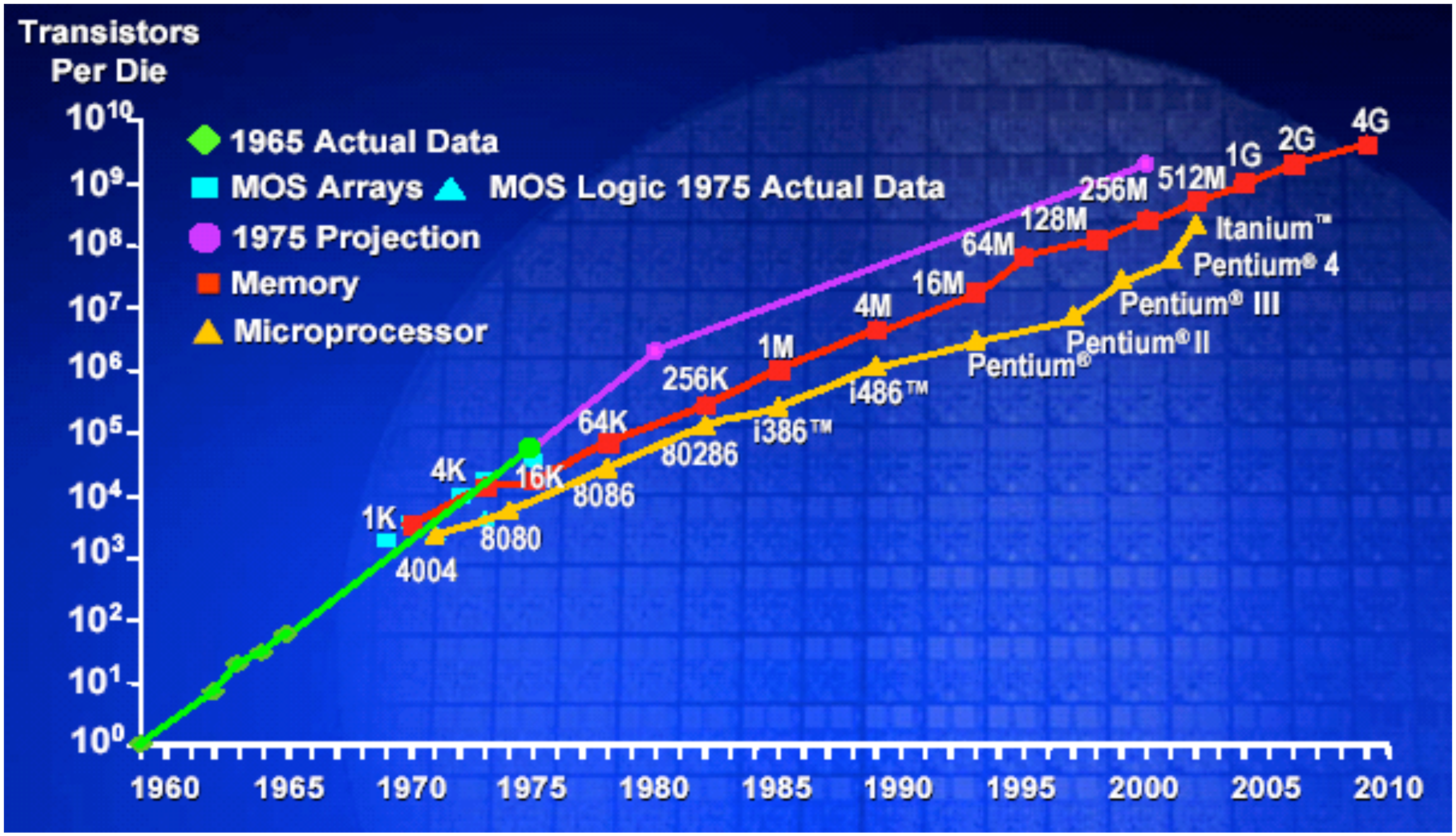
New Application Class

- Monitoring objects and conditions in physical space
- Driven by technology trends
- Will create a new class of applications
- Will drive existing IT systems in new ways

Outline

- Motivation and Context
- Defining Roles and Interests
- Localization Stack
- Results Overview
- Future Outlook

IT growth arising from Moore's Law

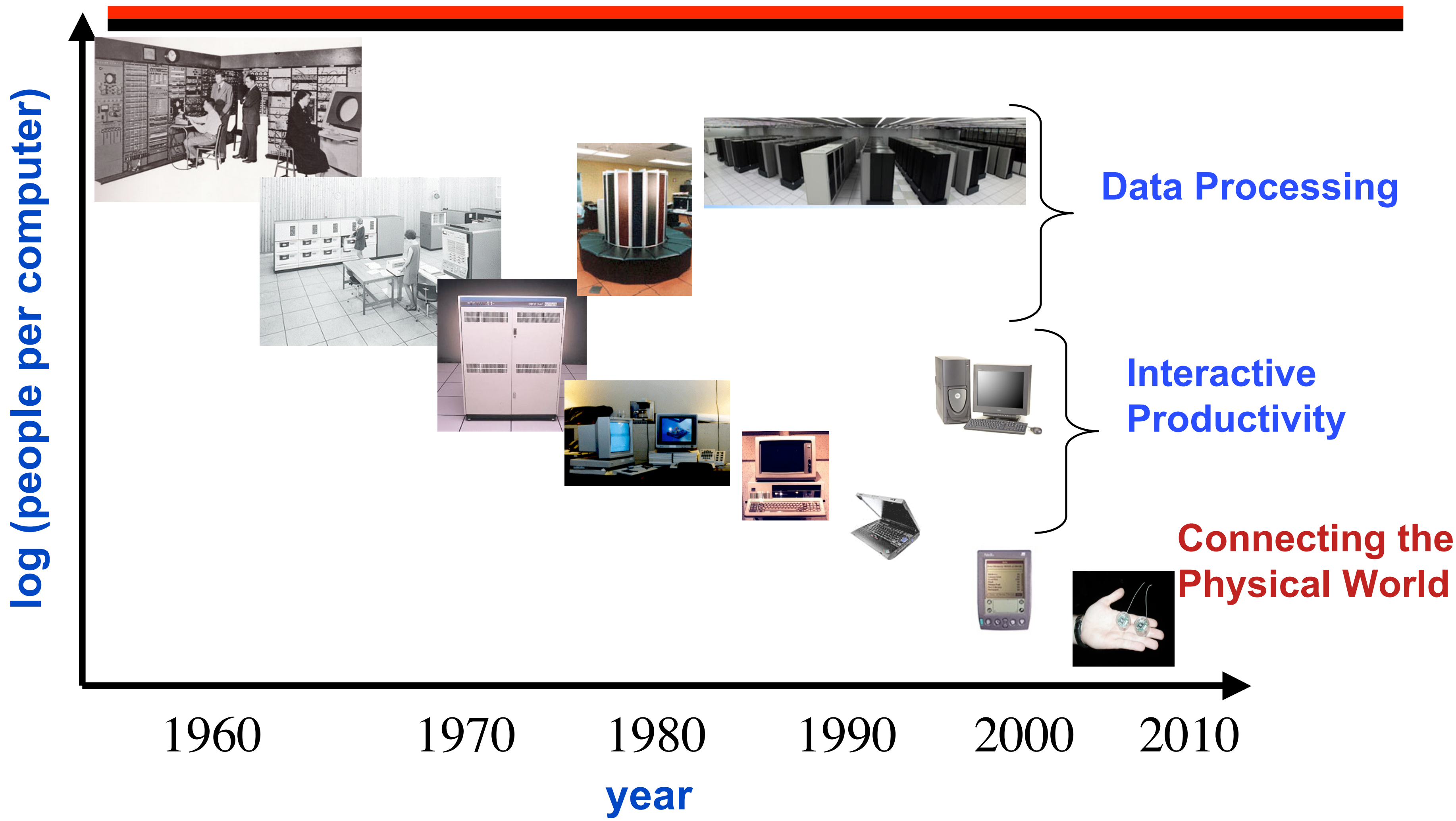


- Law: Transistors per chip doubles every 12-18 months

Impacts of Moore's Law

- Increased power and memory of traditional systems
  - 386,486,Pentium I,II,III,IV, Quad core
- Corollary: Bell's Law
  - Every 10 years a new:
    - Computing platform
    - Industry around the new platform
  - Driven by cost, power, size reductions due to Moore's law

"Bell's Law"


log (people per computer)
Data Processing
Interactive
Productivity
Connecting the
Physical World
1960
1970
1980
1990
2000
2010
year

Turning the Physical World into Information

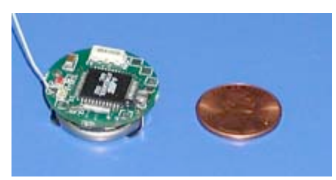
- Truly new capabilities
  - Observe time and space
- New uses for existing platforms

$100,000
server farm

$10,000
server

$1,000
desktop

$100
phone



$10
Active tag&
sensor

$1
Passive tags

Applications

- Classes
  - Monitoring
    - What is happening to people and things in various spaces?
  - Tracking
    - Where is stuff?
  - Security
    - What/who is allowed where, when?
- Sectors
  - Health care
  - Manufacturing
  - Retail
  - Consumer
  - Agriculture

Example 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 my office to InterDigital?
- 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?

My Work: Positioning and Tracking

- Same trends creating cheap wireless communication in every computing device

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

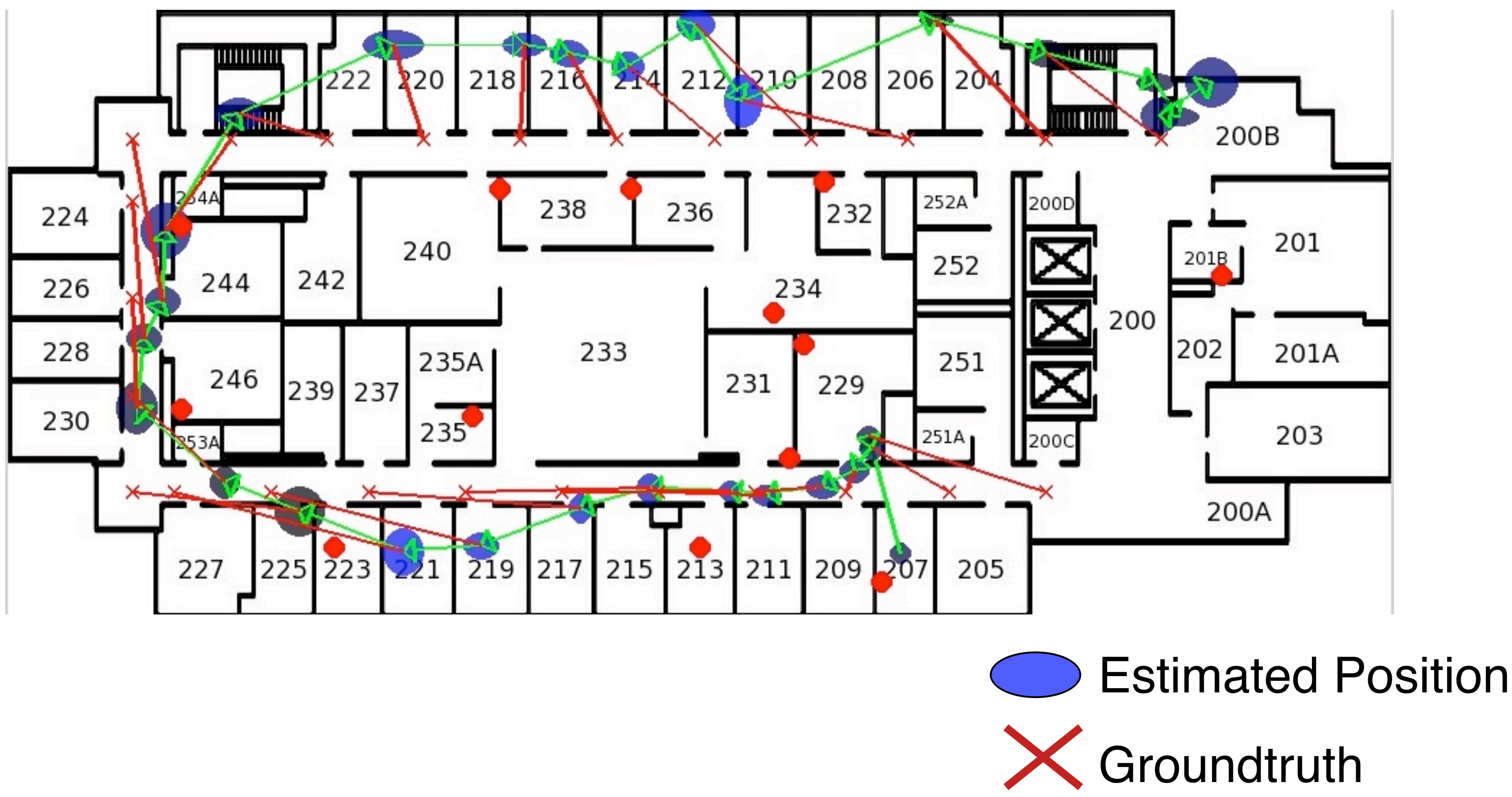
Positioning and Tracking(cont)

- Vision: Real time, physical position of everything
    - Every electronic device (will have wireless)
    - $2 active tag plausible (including battery) (today $15)
    - <$0.25 passive tags
- Don’t we already know how to do this?
    - Many localization systems & algorithms already exist
- Yes, they can localize, but ….
    - Missing the big picture
    - Not general purpose

Opportunity

- Universal
  - Works with any wireless device with little/no modification
  - Supports vast range of performance
    - city, campus, building, room, shelf
  - Localize in any environment the device could be in
    - Outside, inside, under the bed
- General Purpose
  - Resulting position information can be used for a wide variety of applications
  - Returns positions to the people of concern

eeePC Tracking Example



Example 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 campus to the train station?
    - How long will it take me to get to NYC?
- 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?
  - When did the diamond ring move?

Where are we today?

- Analogy: Electronic communication

  1960's Leased lines (problem solved!) ->

  1970's Packet switching ->

  1980's Internetworking ->

  1990's "The Internet":

    Universal, general purpose communication:

    Communication between any 2 devices on the planet

Universal, General purpose localization still open

-like networking in the 1970's and 1980's

Where to start?

Outline

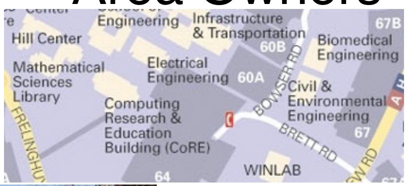
- Motivation and Context
- Defining Roles and Interests
- Localization Stack
- Results Overview
- Future Outlook

General Purpose Localization

- Previous work:
  - Algorithms
  - Specific systems, physical layers, approaches
- Different approach:
  - Define roles and vested interests
  - System stack to support those roles
  - Algorithms and physical layers support the roles

System Level Roles

Area Owners



Network Admins

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verizon

Sprint

Device Owners

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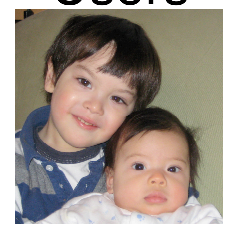
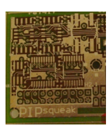
Users



Devices



Application Service Providers

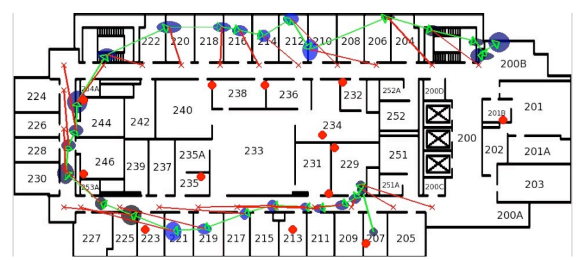
YAHOO!

Google Code

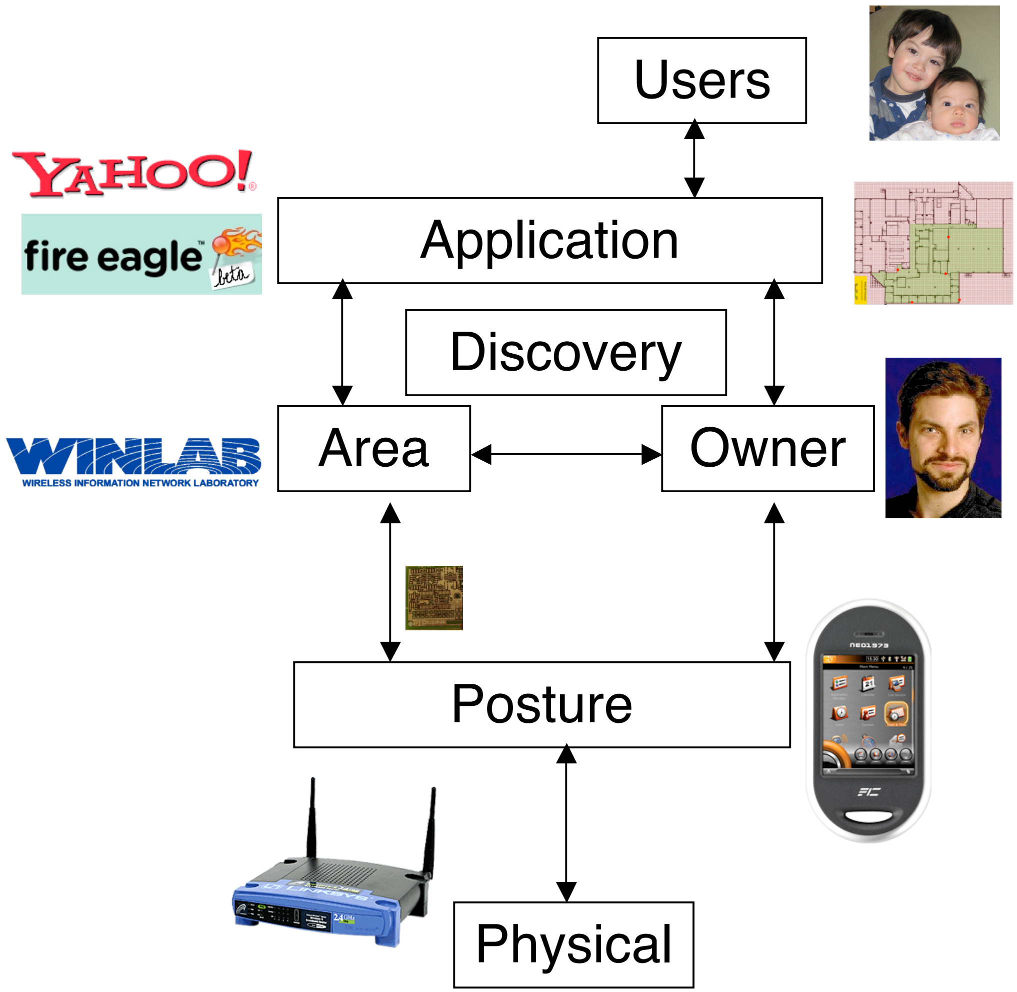
fire eagle beta

Google Maps API

Applications



Location Stack Overview



Need Standards!

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

Layers, Roles & Contracts

- Device owners
  - own the position information about their devices
  - controls access to this info.
- Area owners
  - own the position information about devices in their areas
  - control access to this info
- Application Service Providers
  - Maintain Contract with device, area owners
- Network Administrators
  - Relationship to device owners unclear?

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 ends 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 Real Time Location System (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

- Measure a physical quantity to assist in localization

- Received Signal Strength (RSS)
  - Path loss models
  - Matching on existing maps
- 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

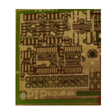
Discovery Protocols

- 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

One system, Two extremes

- Powerful device: Mobile phone
  - Complete environment (Linux, JVM)
  - Multi-modal (WiFi, GPS, 3G, camera)

- Weak device: Active RFID tag
  - Only sends beacons
  - No sensing, storage, no receive



- We have some confidence the localization stack is general purpose if supports both well

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How to Localize?

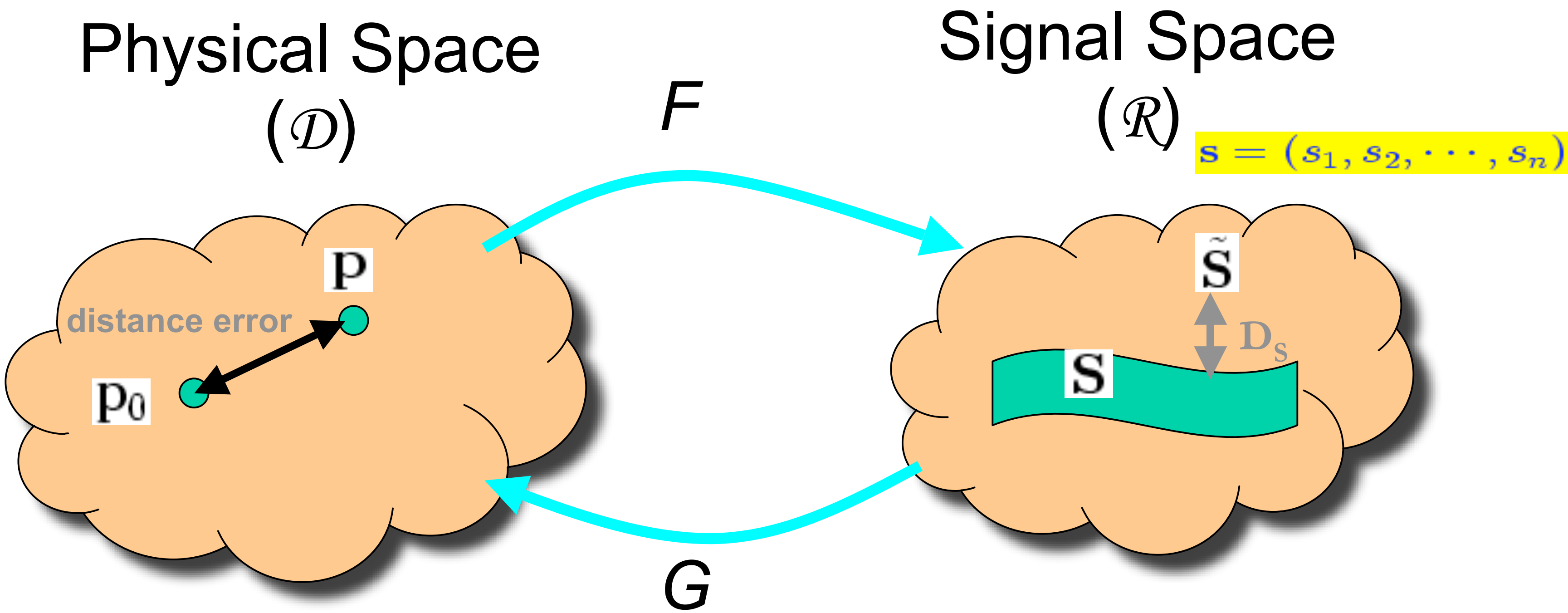
Key distinctions: Model and Observations

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

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



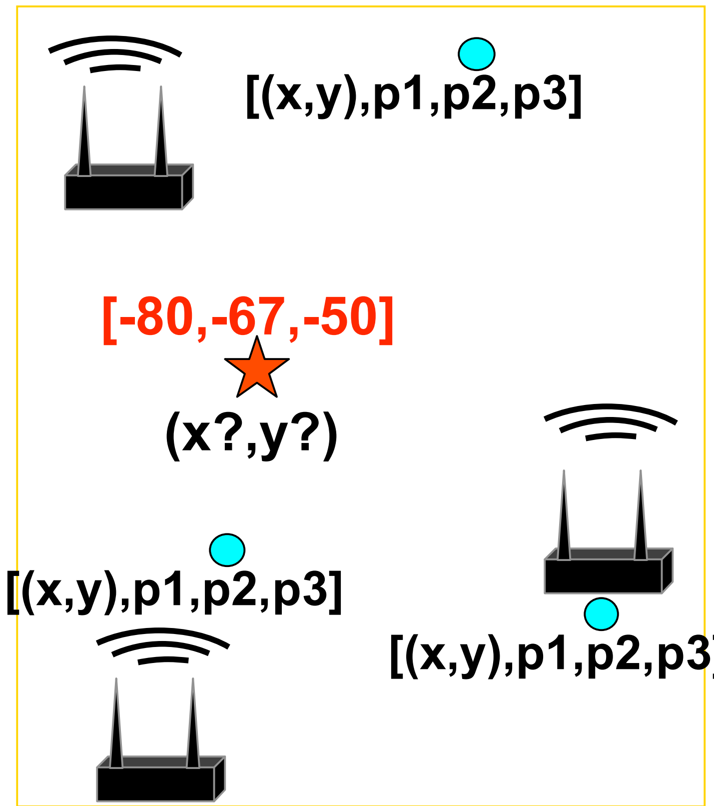
p_0 true location
p estimation

Localization:

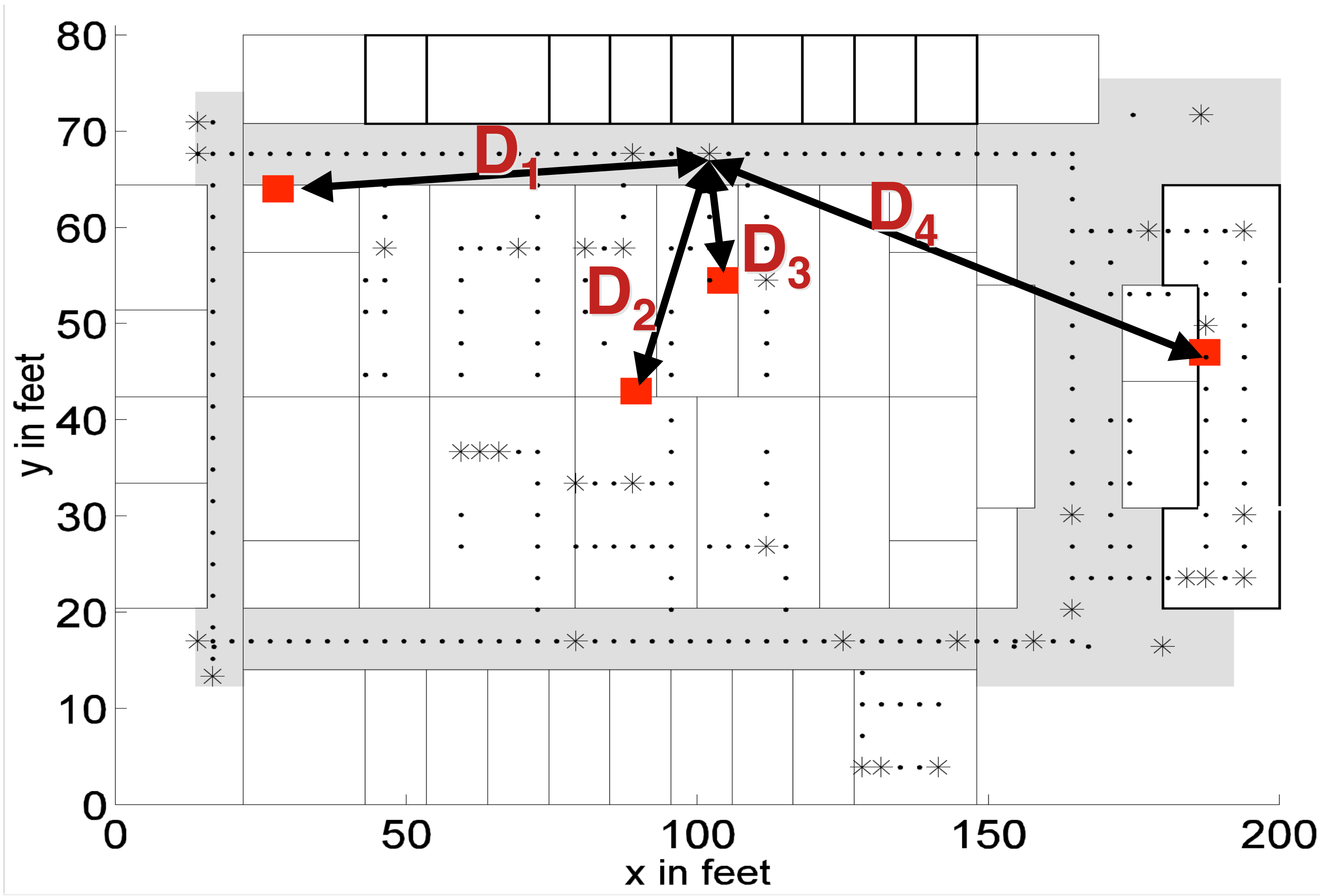
$$\mathbf{p} = G_{alg}(\mathbf{s})$$
$$\tilde{\mathbf{p}} = G_{alg}(\tilde{\mathbf{s}})$$

Generic Approach

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



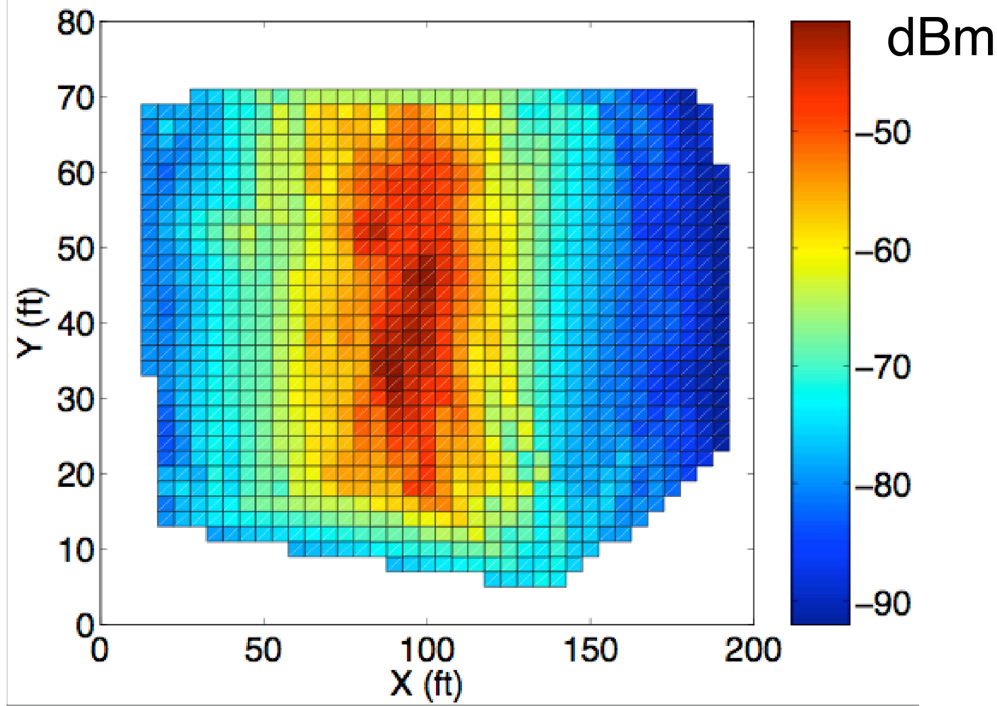
Lateration and Angulation



Scene Matching

- Build a radio map
  [X,Y,RSS_1,RSS_2,RSS_3]
  Training data

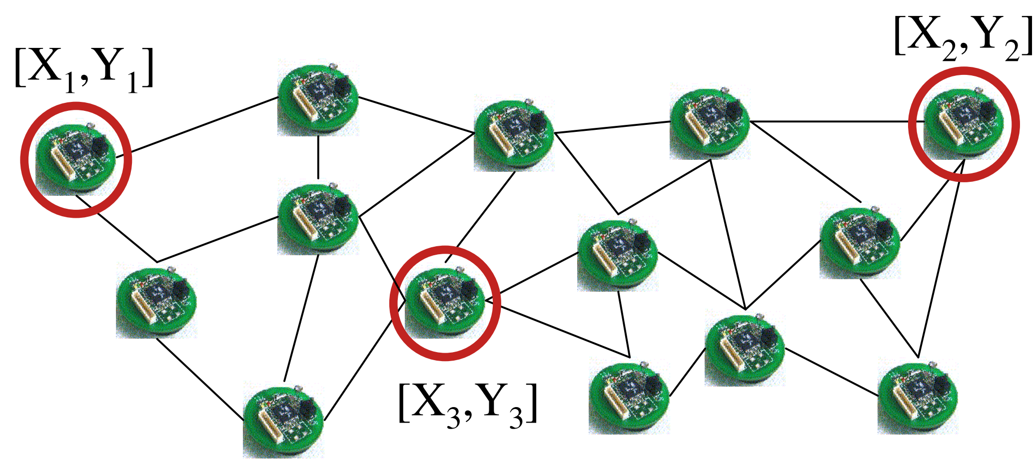
- Classifiers:
  Bayes' rule
  Max. Likelihood
  Machine learning (SVM)
- Slow, error prone
- Have to change when environment changes



Landmark 2

Aggregate Approaches

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



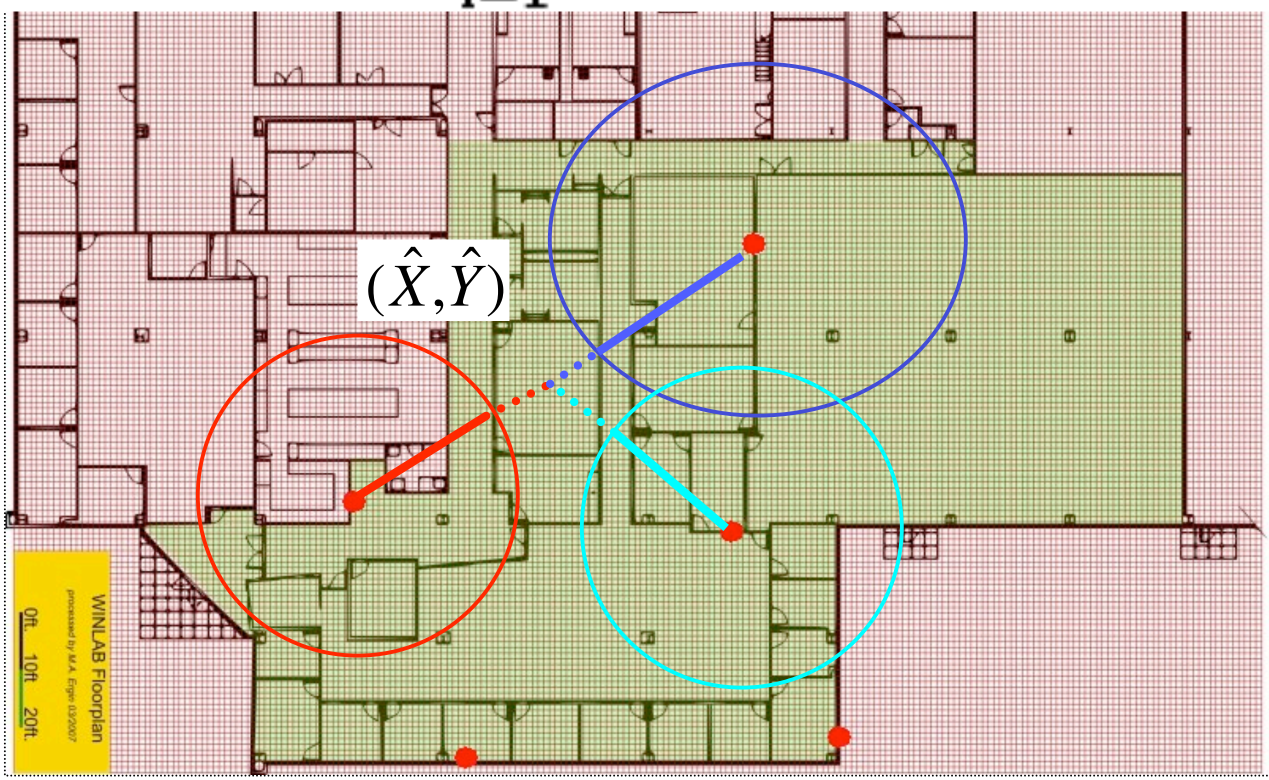
- Formulations:
  - Nonlinear Optimization problem
  - Multi-Dimensional Scaling
  - Energy minimization, e.g. springs
  - Classifiers

Managing Uncertainty

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

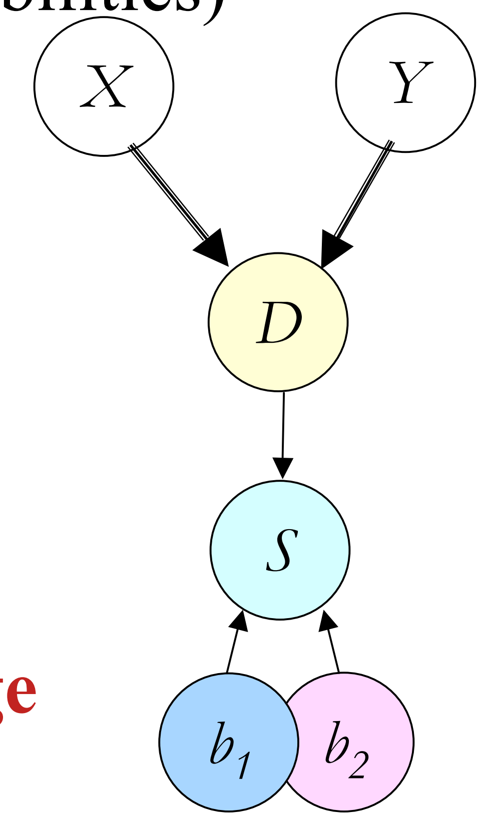
Lateration with Least Squares

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



Lateration with Bayesian Graphical Models

Vertices = random variables
Edges = relationships(conditional probabilities)



Example:

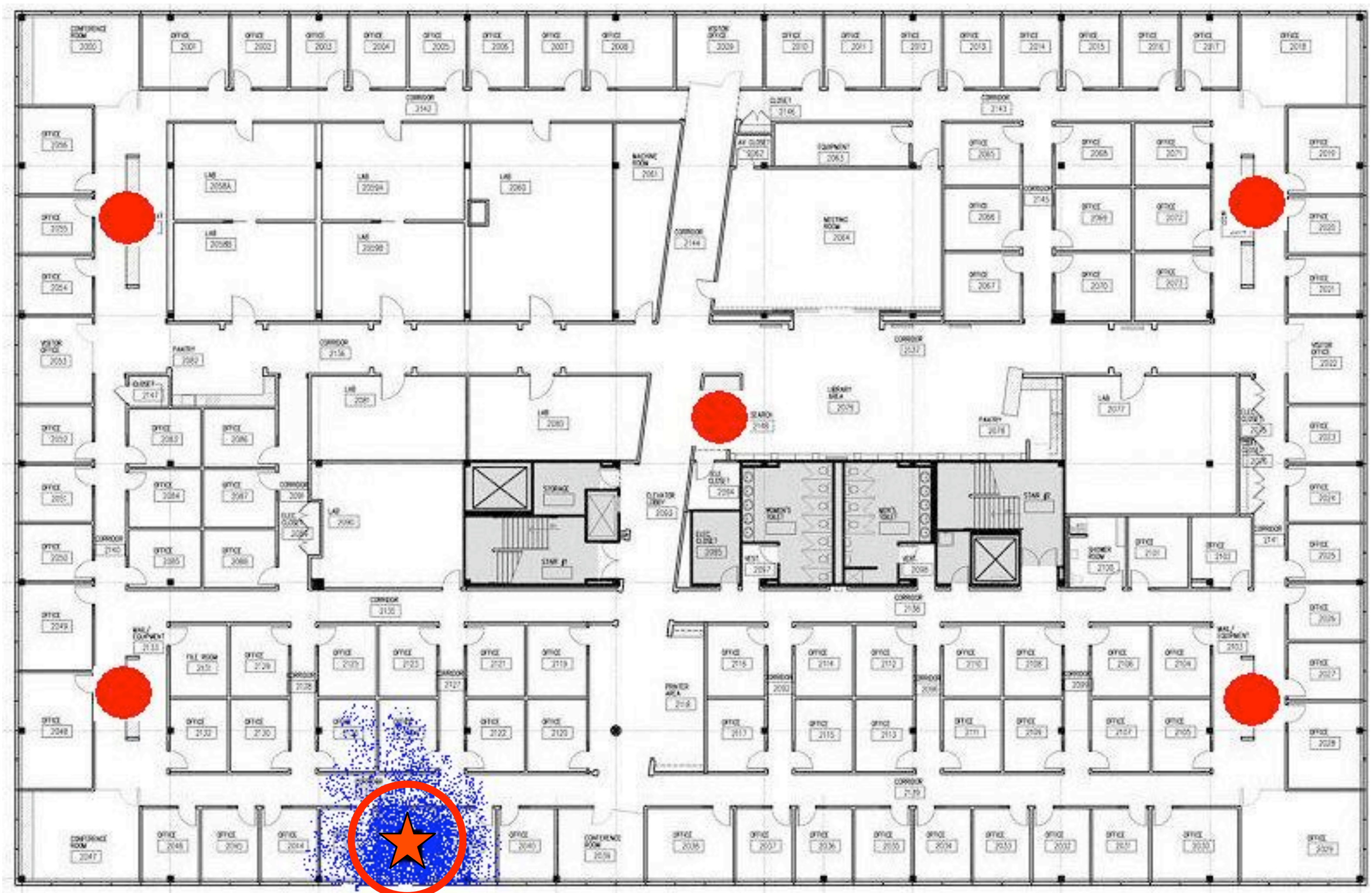
Log-based signal strength propagation

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

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

Can encode arbitrary prior knowledge

Handling Uncertainty using Bayesian Networks and Monte-Carlo Sampling



Performance Metrics

- Accuracy
  - Distance between reported and 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?

Present Results Overview

- Past 16 years --- 1000's of efforts
  - Most have a narrow systems view, focus on alg. or phy.
  - Simulation, or trace-driven simulation
- Aggregate
    - 1/2 1-hop radio range typical.
    - Requires very dense networks (degree 6-8, 12 better)
- Scene matching
    - 802.11, 802.15.4: Room/2-3m accuracy [Elnahrawy 04]
    - Need a lot of training (measured signal maps)
- Lateration and Angulation
    - 802.11, 802.15.4: Room/3-4m accuracy
    - Real deployments worse than theoretical models predict (0.25-1m)
    - Recent results show 1ft accuracy possible with A LOT of resources

Additional Research Work

- Local Area Layer: GRAIL
  - Rich Martin, Eiman Elnahrawy (Kordinate)
- Improving Accuracy:
  - Rich Martin, Marco Gruteser, Yingying Chen (Stevens), Xiaoyan Li (Lafayette)
- Privacy:
  - Marco Gruteser
- Secure localization:
  - Yingying Chen, Wade Trappe
- Low Power Active Tags:
  - Rich Howard, Yangyong Zhang

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Future Challenges

- What are the broader roles & contracts
  - Who needs to be involved to realize universal localization?
  - Who owns the information, how do they control it?
  - Can we build systems to match these expectations?
- Community
  - Fragmentation between ubicomm, WLAN, Telecom
- Location stacks
  - Standards between technologies and roles?
- Increasing accuracy to 1 meter
  - Add to the communication stack's physical layer?
    - Finer clocks, reflectors, angular measurements
  - Additional infrastructure to communication layers?

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

Communities

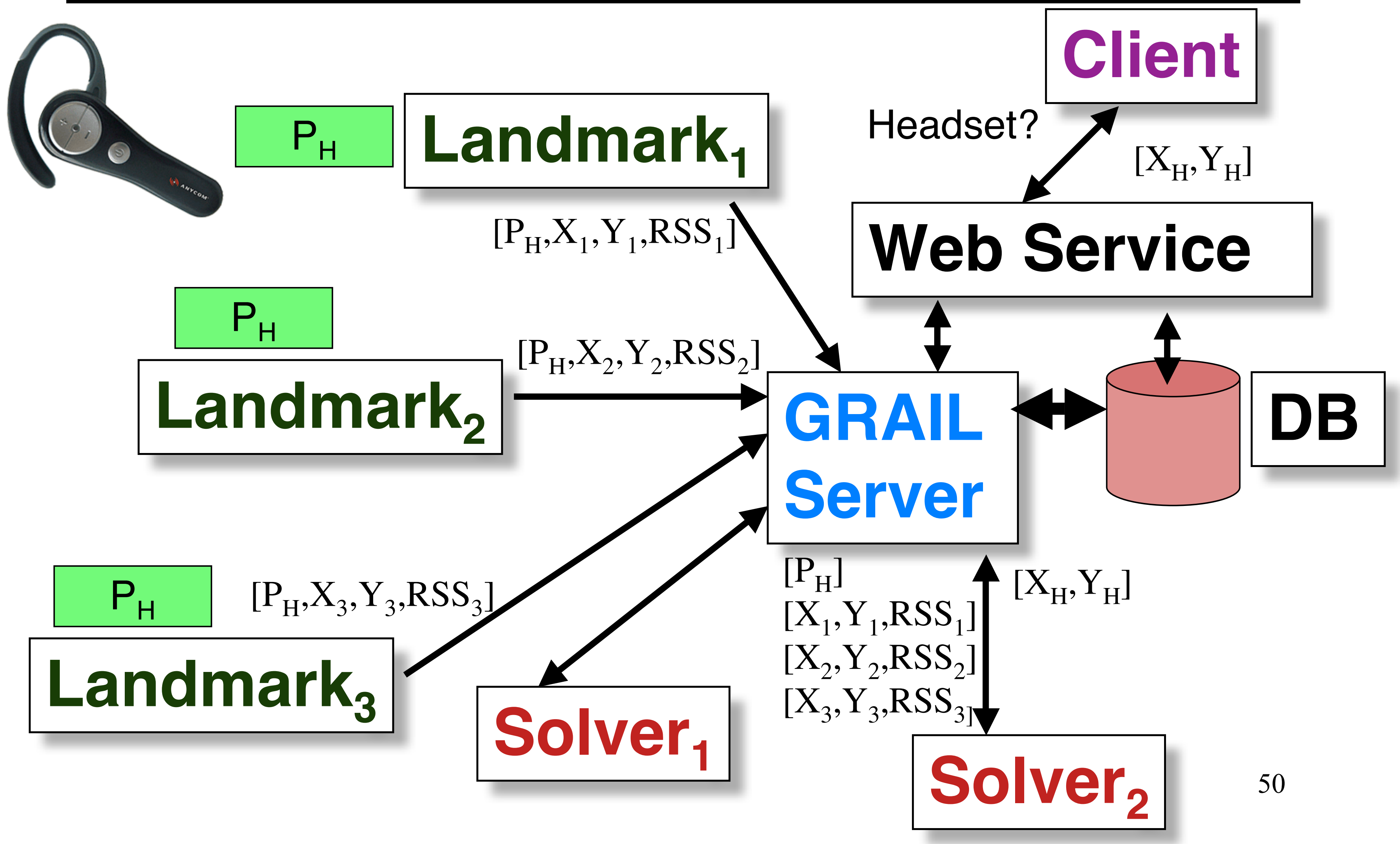
- Ubiquitous Computing
  - Mark Weiser's *Scientific American* article (1991)
- Sensor Networks
  - E.g. Sensys conference
- Mobile Computing
  - E.g. Mobicom, Mobisys conferences
- Local Area Wireless
  - E.g. Infocom, Local Computer Networks (LCN)
- Telecom
  - E.g. Globecom

Increasing Accuracy

Leverage communication as much as possible

- Add to the communication physical layer
  - High frequency clocks
  - Precise echo (measure RTT)
  - Coarse angle estimation (sectors)
- How to expose at layer-2

Area Layer: GRAIL



Communication vs. Localization

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