Localization:
Algorithms and System
Applications of Location Information

- **Location aware information services**
  - e.g., E911, location-based search, target advertisement, tour guide, inventory management, traffic monitoring, disaster recovery, intrusion detection

- **Scientific applications**
  - e.g., air/water quality monitoring, environmental studies, biodiversity

- **Military applications**

- **Resource selection (server, printer, etc.)**

- **Sensor networks**
  - Geographic routing
  - “Sensing data without knowing the location is meaningless.”
  
  [IEEE Computer, Vol. 33, 2000]

- **New applications enabled by availability of locations**
Outline

• Localization in single hop wireless networks
  - Global positioning system (GPS)
  - War-driving

• Localization in multihop wireless networks
  - Sextant
Global Position Systems

- US Department of Defense wants very precise navigation

- In 1973, the US Air Force proposed a new system for navigation using satellites

- The system is known as Navigation System with Timing and Ranging: Global Positioning System or NAVSTAR GPS
GPS Operational Capabilities

Initial Operational Capability - December 8, 1993

Full Operational Capability declared by the Secretary of Defense at 00:01 hours on July 17, 1995
NAVSTAR GPS Goals

- What time is it?
- What is my position (including attitude)?
- What is my velocity?
- Other Goals:
  - What is the local time?
  - What is the distance between two points?
  - What is my estimated time arrival?
GPS System: Overview

• **GPS satellites are essentially a set of wireless base stations in the sky**

• The satellites simultaneously broadcast beacon messages

• A GPS receiver measures time of arrival to the satellites, and then uses “triangulation” to determine its position
GPS System: Overview

• Assume receiver clock is sync’d with satellites

\[ t^{R1} = t^S + \frac{\|p - p_1\|}{c} \]

\[ \|p - p_1\| = c(t^{R1} - t^S) \]

“Triangulation” determines position
Why we need 4 satellites?
GPS System: Overview

• In reality, receiver clock is not sync’d with satellites

Thus need one more satellite to have the right number of equations to estimate clock

\[ t^{R1} = t^S + \frac{d_1}{c} + \delta_{\text{clock-drift}} \]
\[ \|p - p_1\| = c(t^{R1} - t^S - \delta_{\text{clock-drift}}) \]
\[ = c(t^{R1} - t^S) - c\delta_{\text{clock-drift}} \]

called pseudo range
We need to see 4 satellites in GPS

The GPS Navigation Solution
The estimated ranges to each satellite intersect within a small region when the receiver clock bias is correctly estimated and added to each measured relative range.

P. H. Dana 5/10/98
Each satellite timestamp transmission and receivers measure received time

- Time of transmission
- Correct satellite location
- Speed of radio wave
- Time of arrival
GPS Satellite Transmissions

• Requirements
  - all 24 GPS satellites transmit on the same frequencies
  - resistant to jamming
  - resistant to spoofing
  - allows military control of access (selected availability)
  - satellites provide their positions
GPS Multiple Access and Identifying Codes

• All 24 GPS satellites transmit on the same two frequencies BUT use different codes
  - i.e., Modulation used is
    • Direct Sequence Spread Spectrum (DSSS) and
    • Code Division Multiple Access (CDMA)
Navigation Message

• To compute position one must know the positions of the satellites

• Navigation Message (37,500 bits) - transmitted on both L1 and L2 at 50 bps

• Navigation message consists of:
  - satellite status to allow calculating position
  - clock information
GPS Identifying Codes

- **Two types of clock signals**
  - *C/A Code* - Coarse/Acquisition Code available for civilian use on L1 provides 300 m resolution
  - *P Code* - Precise Code on L1 and L2 used by the military provides 3 m resolution
  - Encrypted P Code provides selected availability and anti-spoofing
GPS Messages

GPS SATELLITE SIGNALS

- L1 CARRIER 1575.42 MHz
- C/A CODE 1.023 MHz
- NAV/SYSTEM DATA 50 Hz
- P-CODE 10.23 MHz
- L2 CARRIER 1227.6 MHz

Mixer
Modulo 2 Sum

L1 SIGNAL
L2 SIGNAL
GPS Receiver

• Typical receiver: C/A code on L1

• During the “acquisition” time you are receiving the navigation message also on L1

• The receiver then reads the timing information and computes the “pseudo-ranges”
Denial of Accuracy (DOA)

- The US military uses two approaches to prohibit use of the full resolution of the system
  - Anti-Spoofing (AS) - P-code is encrypted
  - Selective availability (SA)
    - noise is added to the clock signal
    - the navigation message has “lies” in it
GPS Operation

• **Segments (components)**
  - space segment: the constellation of satellites
  - control segment: control the satellites
  - user segment: users with receivers
Space Segment
Space Segment

- System consists of 24 satellites in the operational mode
  - 21 in use
  - 3 other satellites are used for testing
- Altitude: 20,200 Km with periods of 12 hr.
- Current Satellites: Block IIR- 25,000,000 2000 KG
- Hydrogen maser atomic clocks
  - these clocks lose one second every 2,739,000 million years
GPS Orbits

GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination
Control Segment

Master Control Station is located at the Consolidated Space Operations Center (CSOC) at Flacon Air Force Station near Colorado Springs.
CSOC

- Track the satellites for orbit and clock determination
- Time synchronization
- Upload the Navigation Message
- Manage Denial Of Availability (DOA)
GPS: Summary

• GPS is among the simplest localization system in terms of topology

• Limitations of GPS
  - Hardware requirements vs. small devices
  - Obstructions to GPS satellites common
    • Each node needs LOS to 4 satellites
    • LOS hard to achieve in many environments, e.g., urban canyon, indoors, and underground
  - GPS jammed by adversaries
  - GPS spoofing
    • Proof of concept: Luxury yacht “White Rose” misdirected from Monaco to the island of Rhodes
    • Suggested it caused capture of a Lockheed RQ-170 drone aircraft in northeastern Iran
What other signals to use for localization?
Signals for localization

- RF signal: WiFi, bluetooth, sensor, UWB
- Acoustic signal
- Ultrasound
- Light
- Magnetic field
- IMU
Signals for localization

• RF signal: WiFi, bluetooth, sensor, UWB
• Acoustic signal
• Ultrasound
• Light
• Magnetic field
• IMU
RADAR: An In-building RF based User Location Tracking System
Motivation

- Location-aware services are key ingredient of mobile computing

- Determining user location is a prerequisite to building such services

- Solution designed for the outdoors (e.g., GPS) are ineffective indoors
Approach

• **Ideas**
  - Leverage *existing* infrastructure
  - Use an off-the-shelf RF wireless LAN

• **Several advantages**
  - WLAN deployed primarily to provide data connectivity
  - Software adds value to wireless hardware
  - Better scalability and lower cost than dedicated technology
RADAR

• **Key idea**
  - Signal strength matching
  - Why?

• **Offline calibration**
  - Tabulate \langle\text{location}, \text{SS}\rangle\text{ to construct radio map}

• **Real-time location & tracking**
  - Extract SS from base station beacons
  - Find table entry that best matches the measured SS
Construct a Radio Map

**Empirical method**
- Measure SS at various locations using BS beacons
- Record SS along with corresponding coordinates
  - User orientation need to be included too!
  - Tuples of the form \((x,y,z,d,s_1,...,s_n)\)

**Mathematical method**
- Compute SS using a simple propagation model
- Factor in free space loss and wall attenuation
- Apply Cohen-Sutherland line clipping algorithm on building layout
- More convenient but less accurate
Determine Location

- Find nearest neighbor in signal space (NNSS)
  - Default metric is Euclidean distance
- Physical coordinates of NNSS $\rightarrow$ user location
- Refinement: $k$-NNSS
  - Average the coordinates of $k$ nearest neighbors

- $N_1, N_2, N_3$: neighbors
- $T$: true location of user
- Guess based on averaging
Experimental Setting

- Digital RoamAbout (WaveLAN)
- 2.4 GHz ISM band
- 2 Mbps data rate
- 3 base stations
- $70 \times 4 = 280$ (x,y,d) tuples
How good an indicator of location is signal strength?
Base line performance

Median error distance is 2.94 meters
Performance with averaging

Median error distance is 2.13 meters when averaging is done over 3 neighbors.
How extensive the Radio Map should be

Diminishing as the number of physical points mapped increased
Signal Propagation Model

\[ P(d)[dbm] = P(d_0)[dbm] - 10n \log(d/d_0) - nW*WAF \]

\[ \& \begin{align*}
\text{for } nW < C \\
\text{for } nW >= C
\end{align*} \]
Accuracy

Median error distance is 4.94 m compared to 2.94 m with empirically constructed radio map and 8.16 m with nearest base station method.
Summary

• Determine user location via signal strength matching

• Radio map constructed via empirical measurements

• Median error 2-3 meters with empirical map

• Leverages existing wireless LAN infrastructure
Sextant: A Unified Node and Event Localization Framework Using Non-Convex Constraints

S. Guha, R. N. Murty, E. G. Sirer
Localization in Multihop Wireless Networks

Given:
- Set of \( n \) points
- Positions of \( k \) of them known
- Distances between \( m \) pairs of points \((m \leq n)\)

Find:
- Positions of points which can be determined

Illustration:
- Find locations to satisfy distance constraints
- Typically under-constrained
- How to address the problem?
Localization in Multihop Wireless Networks

Given:
- Set of $n$ points
- Positions of $k$ of them known
- Distances between $m$ pairs of points

Find:
- Positions of points which can be determined

Illustration:

Find locations to satisfy distance constraints
- Typically under-constrained
- Modify the graph to avoid being under-constrained
- Find most likely positions
- Find all possible positions
Localization in Multihop Wireless Networks

**Given:**
Set of $n$ points  
Positions of $k$ of them known  
Distances between $m$ pairs of points

**Find:**
Positions of points which can be determined

Illustration:
Find locations to satisfy distance constraints
Typically under-constrained
- Modify the graph to avoid being under-constrained
- Find most likely positions
- Find all possible positions

node with known position (*beacon*)
node with unknown position
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distance measurement
Node Localization

- The accuracy of localization depends on how we extract constraints
- Solve a set of constraints to produce estimated location set, $\varepsilon_A$
- What constraints can we extract?
Constraint Extraction

• **Absolute constraints on landmark nodes**
  - explicit coordinates or regions, e.g. from GPS

• **Relative constraints**
  - Mere connectivity information between nodes
  - Two radii to handle irregular wireless transmission zones
    • How?
  - Can incorporate rss and angle info.
    • How?
Handling Irregular Wireless Propagation

Wireless Radio

Boolean packet-received / packet-not-received.

- All reachable nodes $\leq R$ away
- All unreachable nodes $\geq r$ away
**Constraint Extraction**

- **Positive constraints**
  - *A must be located inside region* $X$
  - intersection, $\varepsilon_A = \varepsilon_A \cap X$

- **Negative constraints**
  - *A cannot be located inside region* $X$
  - subtraction, $\varepsilon_A = \varepsilon_A \setminus X$
Constraint Extraction (Cont.)

• **Maximal wireless coverage region**
  - union of all circles $M^W_B$ of radius $R$

• **Assured wireless coverage region**
  - intersection of all circles of radius $r$
Node Localization
Node Localization

Intersection of Positive Information
Node Localization

Negative Information
Node Localization

Subtraction of Negative Information
Node Localization

Combining Positive and Negative Information
Node Localization

Each Node $x$
- Location Estimate: $\mathcal{E}_x$
- Positive Constraint: $\mathcal{P}_x$
- Negative Constraint: $\mathcal{N}_x$
- Set of positive constraints: $\Gamma_x$
- Set of negative constraints: $\Theta_x$

Invariant

$$\mathcal{E}_x = \bigcap_{p \in \Gamma_x} p \setminus \bigcup_{n \in \Theta_x} n$$
Any issue?
How to represent a region?
Represent Regions

• **Bezier regions**
  - polygons enclosed by knotted Bezier curves
    • each curve is defined by 4 control points
  - expressive and compact
    • handle shapes that are non-convex and/or have holes
  - enable efficient region operations (e.g., union, intersect, subtraction)
Protocol

- **Neighborhood discovery**
  - Nodes transmit periodic beacons
  - Threshold beacon reception required for boolean connectivity

- **Each node $B$ keeps track of**
  - its estimated location set $\epsilon_B$
  - sets of positive constraints and negative constraints

- **Propagates constraints via Gossip**
  - Disseminate constraints as long as they are useful
  - Positive information -- used only at first hop
  - Negative information -- used within the first few hops
Implementation

• Implementation
  - Implemented on MICA-2 motes, laptops and PDA
  - About 2kB of storage per node
  - About 80kB data transmitted per node until convergence

• Setup
  - 50 MICA2 motes placed in a grid pattern
  - Landmarks chosen at random
  - 80% packet reception threshold chosen for connectivity
Evaluation Setup

• Test-bed experiment
  - 50 motes with 49 on a 7x7 grid and one as an access point
    • inter-node separation is 61cm on the grid
  - 30% landmarks randomly chosen
  - $r = 121\text{cm}$, $R = 183\text{cm}$, $S = s = 61\text{cm}$
  - TTL = 3

• Simulation
  - nodes randomly deployed over 366cmx366cm
Evaluation Methodology

• Compare against three approaches
  - Triangulation: centroid of neighbor nodes
  - Single-hop: no transitive dissemination
  - Positive-constraints: no negative information

• Error metrics with Monte Carlo technique
  - Randomly choose sample points in the region
  - Pick the point that minimizes the average distances to other sample points
Results: Node Localization

Sextant locates more nodes for a given accuracy requirement.
Sextant requires fewer landmarks for a given accuracy requirement.
Results: Event Localization

Sextant locates more events accurately.
Results: Event Localization (Cont.)

The performance of Sextant is effective over a wide range of sensing range values.
Conclusions

- Sextant achieves high accuracy and scalability
  - Conservative and comprehensive extraction of negative as well positive constraints
  - Transitive dissemination of constraints
  - Explicit representation of regions using Bezier curves
  - Use of events to refine node location
- Sextant unifies node and event localization in the same framework
- Evaluation via simulation and experiments
  - Deals well with violations of simplistic assumptions
  - Implemented on MICA-2 motes, PDAs and laptops
Comments

• **Pros**
  - Extract negative constraints
  - Use region to represent location
  - Use efficient replication of regions

• **How to improve Sextant?**
Summary

• Localization in single-hop and multihop wireless networks

• Ongoing work on localization
  - Device free localization
  - Localization in mobile networks
  - Combine other signals to improve localization accuracy
  - Gesture recognition, activity recognition
Beyond Localization

• **Xbox Kinect**
  - [https://www.youtube.com/watch?v=pzfpXAbQ61U](https://www.youtube.com/watch?v=pzfpXAbQ61U)

• **Audio based tracking**
  - [https://www.youtube.com/watch?v=OJuTJixq_Zs](https://www.youtube.com/watch?v=OJuTJixq_Zs)

• **WiFi based tracking**

• **Light based tracking**

• **Google Soli 60 GHz based tracking**
  - [https://www.youtube.com/watch?v=OQNzZfSsPc0](https://www.youtube.com/watch?v=OQNzZfSsPc0)