CS7351 传感系统原理与设计

Principles and Design of Sensing Systems

位置感知 & 定位技术

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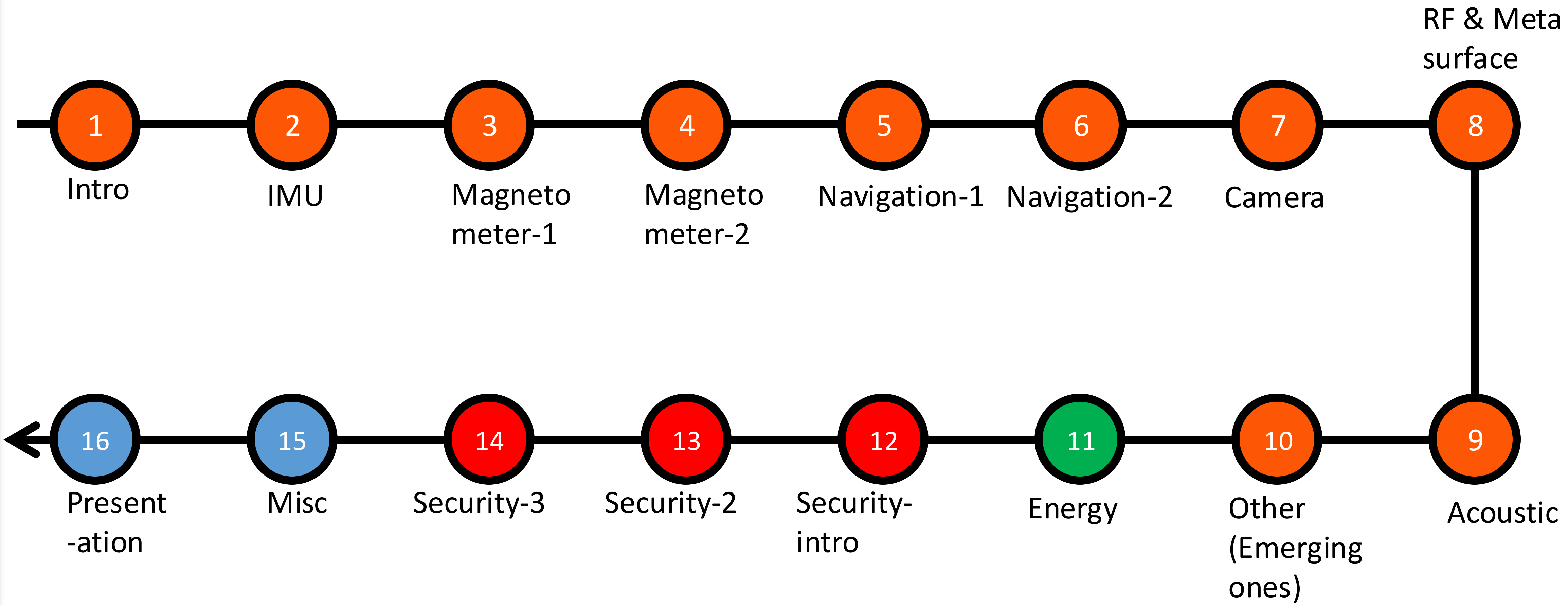
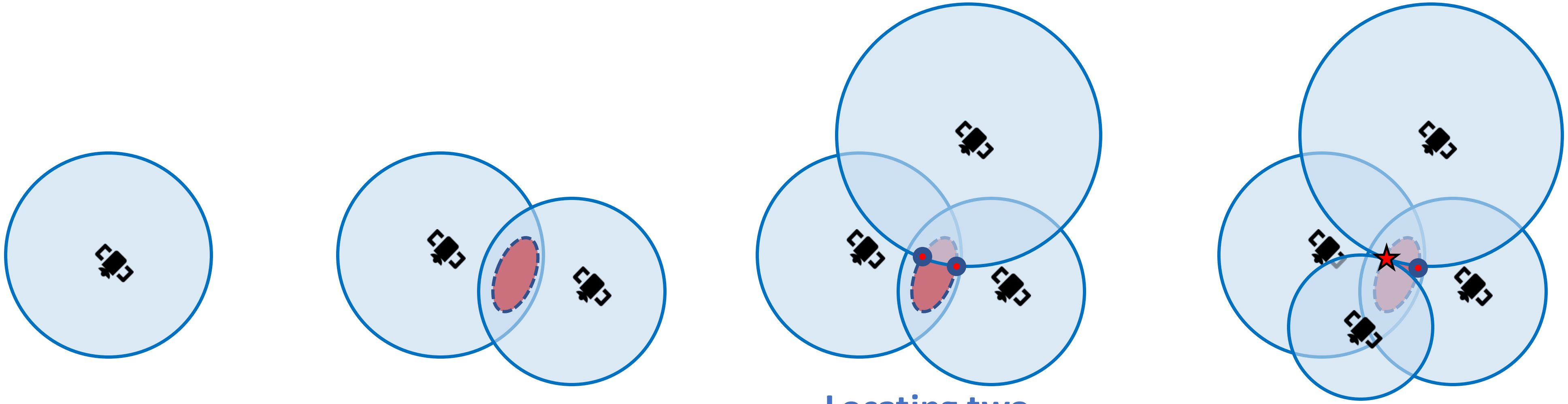
Lecture Roadmap



Why Need 4 Satellites for Localization?



Finding a sphere Locating a surface Locating two points Finding the point

- Trilateraization

接收设备时间

$$(x-x_1)^2+(y-y_1)^2+(z-z_1)^2=c(t_{rx}-t_{tx,1})$$ 卫星，铯原子钟时间

$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=c(t_{rx}-t_{tx,2})$$

$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=c(t_{rx}-t_{tx,3})$$

$$(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=c(t_{rx}-t_{tx,4})$$

直接使用 t_{rx} 误差会很大!

Outline

- Localization Background and Principles
- Global Navigation Satellite System (GNSS)
- Indoor Localization
    - Overview
    - Fingerprinting
    - Ultra-wideband
    - Other techniques

Goal of indoor localization

- The goal is positioning *things* within a building
  - Where can I find **X**?
  - **X**: where am I located?
  - **X** and **Y**: are we near each other?

Localization Classes

- **Absolute** location
  - X, Y, Z position based on already known infrastructure locations
    - For example, GNSS and base station
  - Installed localization hardware known as *anchors*

- **Relative** location
  - Position relative to other devices
  - Might only need a few devices
  - For example, how far is the smartphone from the computer?

Localization knowledge

- What kind of a result is useful?
  - You are at {15, 27.5, 1}
  - You are in Room 224

  ……
  - Depends on the application

- Additional systems on top of the localization method can translate between location representations

Accuracy notation

- "40 cm median accuracy"
  - Majority of measurements are within 40 cm of reality!
  - *What about the other half?*

- 90^{th} percentile error is often more important for real-world applications

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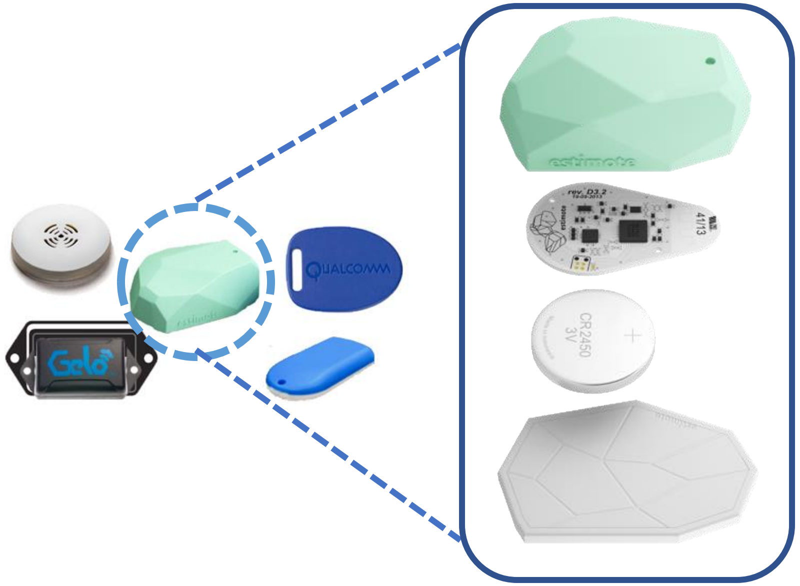
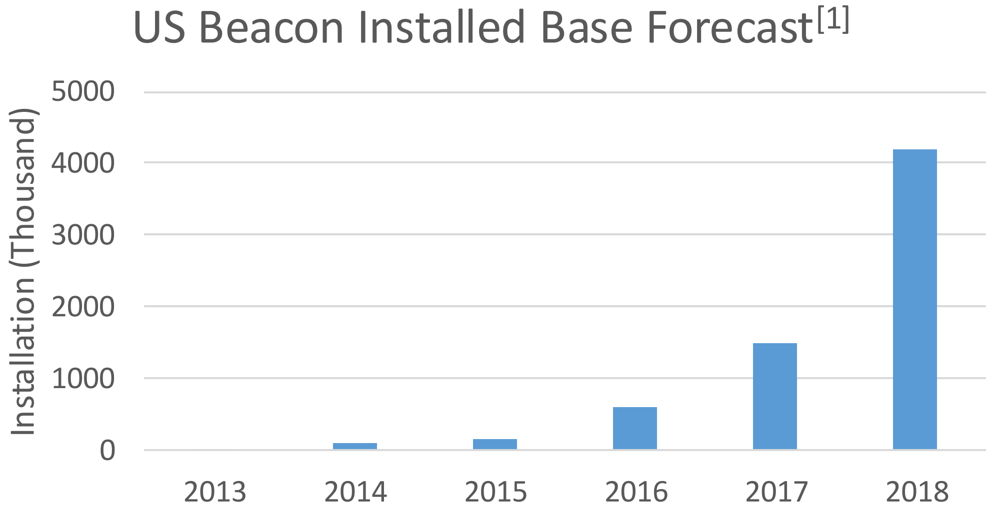
RSSI Ranging with Bluetooth low-energy (BLE) Signal

Dongyao Chen, Kang G. Shin, Yurong Jiang, and Kyu-Han Kim. 2017. Locating and Tracking BLE Beacons with Smartphones. In Proceedings of the 13th International Conference on emerging Networking EXperiments and Technologies (CoNEXT '17). Association for Computing Machinery, New York, NY, USA, 263–275. https://doi.org/10.1145/3143361.3143385

Background: BLE Beacon

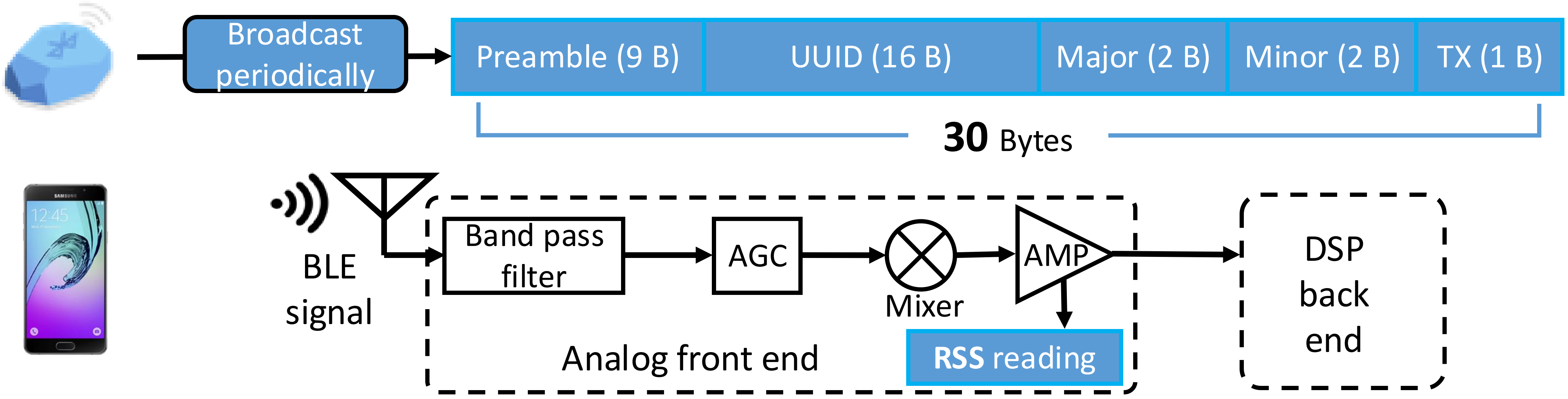




- BLE beacon: a class of BLE devices that broadcast their IDs to nearby devices
  - Light-weighted, low-power design (2-year battery life)
- Main usage scenario: measuring proximity in a retailor store
- Estimated market of **$52B** by year 2020

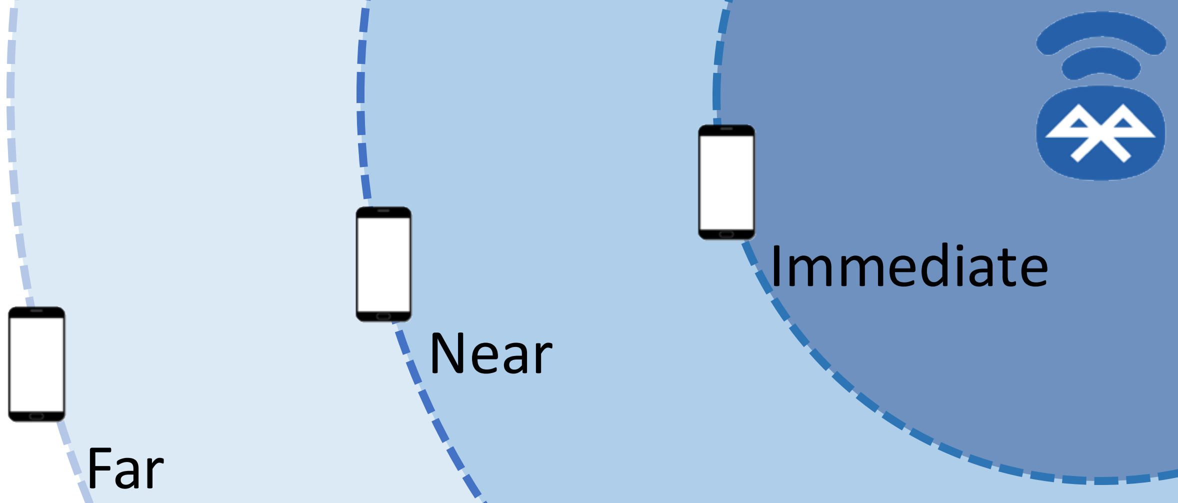
[1] http://www.businessinsider.com/google-looks-to-secure-bluetooth-beacon-communications-2016-4

Background: Proximity Sensing App



- User's smartphone can estimate the **proximity** of neighboring BLE beacons by analyzing **RSS**

Background: Proximity Sensing App



- User's smartphone can estimate the **proximity** of neighboring BLE beacons by analyzing **RSS**
- Provide rough proximity information of surrounding beacons
  - E.g., ***immediate***, ***near***, and ***far***

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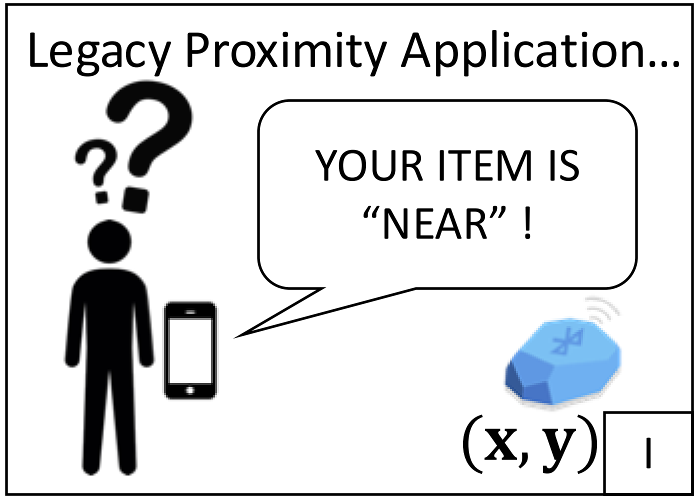
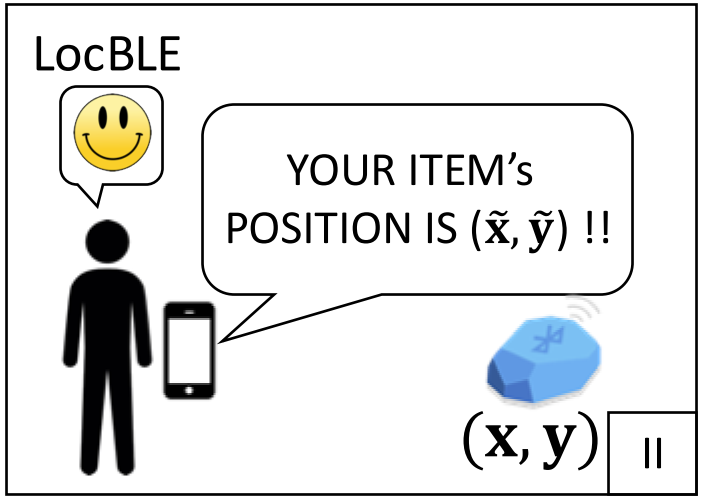
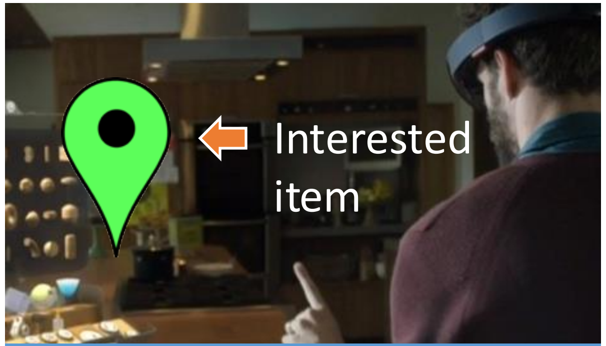




- User’s smartphone can estimate the **proximity** of neighboring BLE beacons by analyzing **RSS**
- Provide rough proximity information of surrounding beacons
  - E.g., ***immediate***, ***near***, and ***far***
- Usability is limited – only proximity information is provided

Benefits from Estimating Beacons’ Location

Find item



Highlight item in AR

Infer user’s relative location

“Last meter” navigation

- Use-cases
  - Locate lost item(s)
  - Highlight interested item(s) in AR
  - Infer user’s relative location
  - “Last meter” navigation: fine-grained localization for augmenting GPS navigation

Locating BLE Beacons – why it's Challenging?

- AC powered RF transmitter
- Bandwidth: 40 MHz for 802.11 n
- Connectivity: both send and receive

v. s.

- < **500 mA·h** battery designed for 3-year lifetime
- Bandwidth for BLE signal **2 MHz** ea. sub-channel
- Connectivity: only send

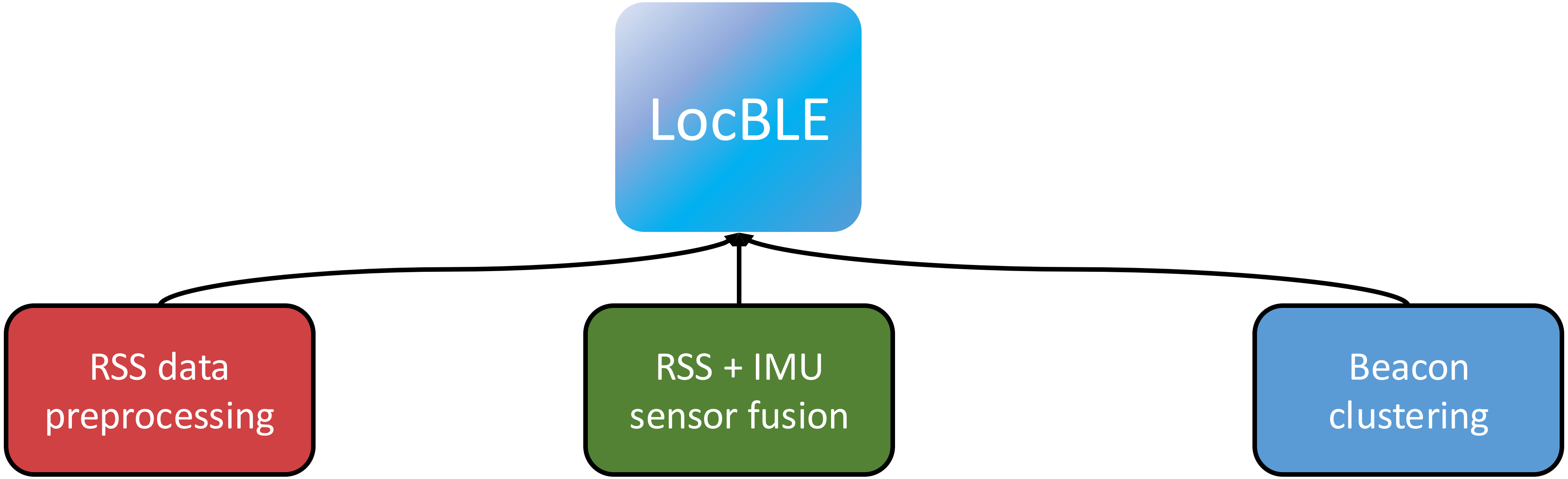
- Constraints stem from the nature of BLE beacon signal
  1. Limited transmission ***power*** – for sustaining years of usage
  2. Narrow ***bandwidth*** – only **2 MHz** bandwidth for each sub-channel
  3. Limited ***connectivity*** – only capable of sensing BLE advertisements

Goal: Locating BLE Beacon on Smartphones

LocBLE

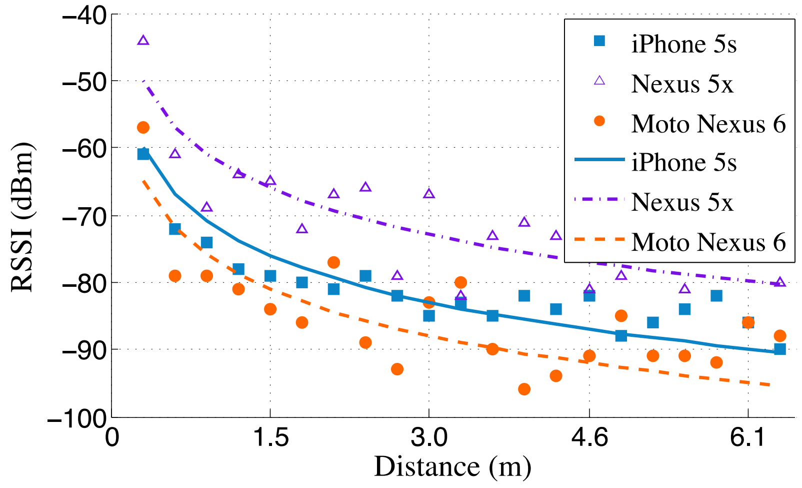
- Smartphone-based application for estimating location of nearby commodity BLE beacons

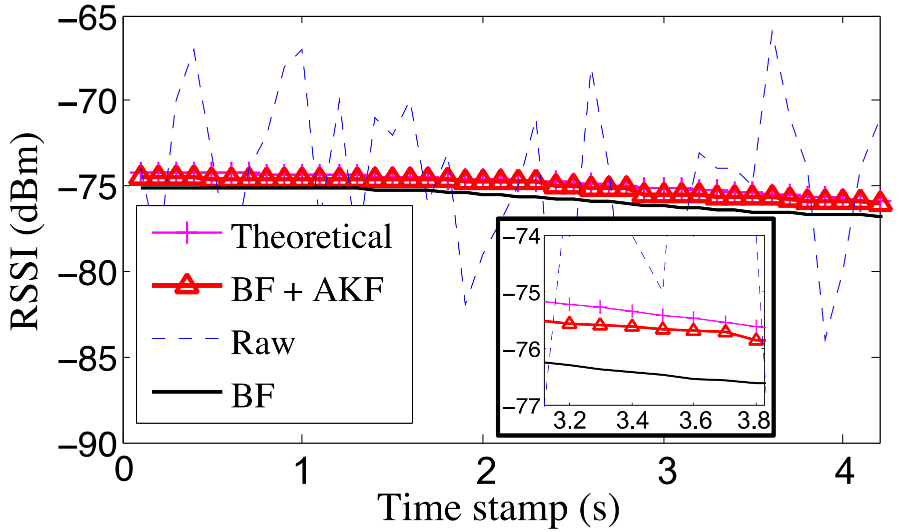
Goal: Locating BLE Beacon on Smartphones



- Smartphone-based application for estimating location of nearby commodity BLE beacons
- **3** key modules

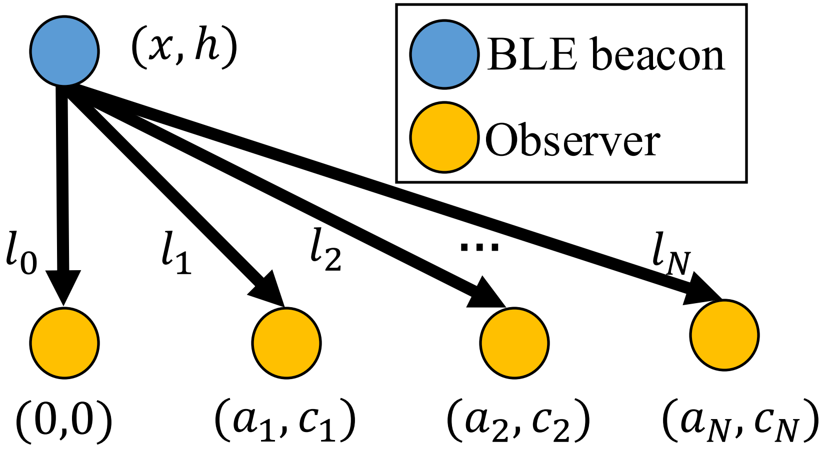
I: Mitigate RSS Signal Fluctuation





- RSS – distance (path loss) model: $\mathrm{RSS} = \Gamma - 10n\log(d)$
- Estimate **path loss exponent** n and **path loss offsets** Γ
  - Path loss exponent – varies with environment
  - Path loss offsets – vary with environment and hardware configuration(s)

II. RSS + IMU Sensor Fusion



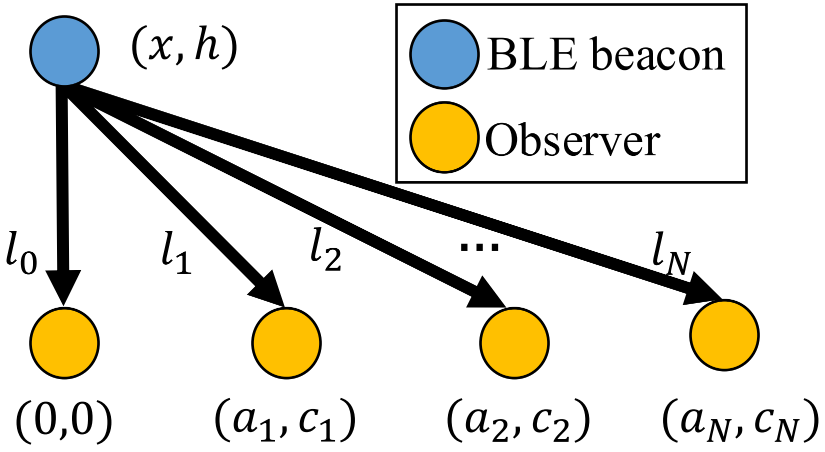
- Problem formulation: RSS reading + user's movement

Measured by BLE receiver

$$\begin{cases} \boxed{\mathrm{RS}} = \boxed{\Gamma(e)} - 10\boxed{n(e)}\log(l_0) \\ l_0^2 = \boxed{x}^2 + \boxed{h}^2 \end{cases}$$

Estimate target

II. RSS + IMU Sensor Fusion



- Problem formulation: RSS reading + user's movement

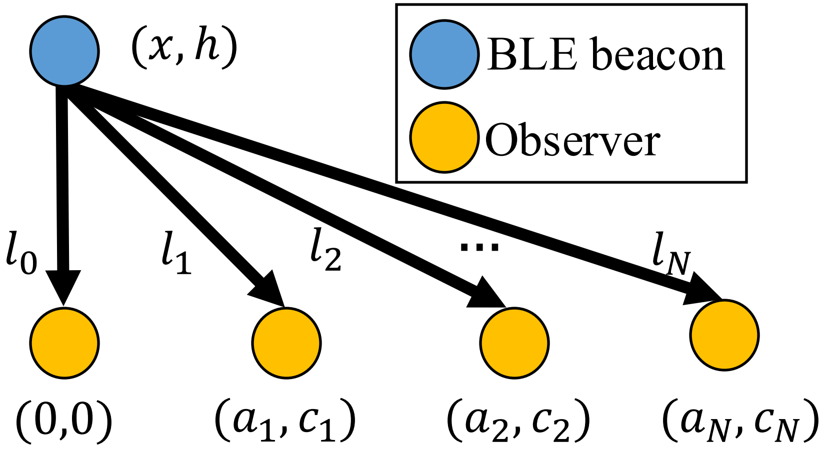
Measured by BLE receiver

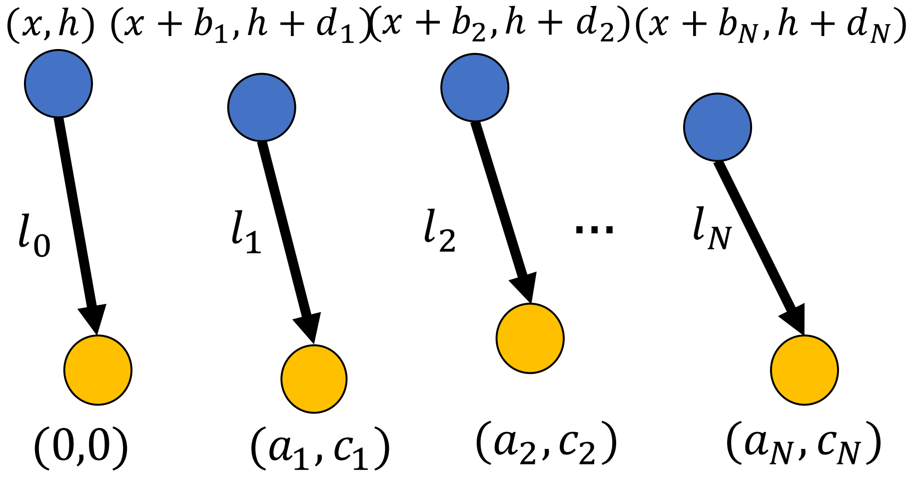
$$\begin{cases} \boxed{\mathrm{RS}} = \boxed{\Gamma(e)} - 10\boxed{n(e)}\log(l_0) \\ l_i^2 = (\boxed{x} - \boxed{a_i})^2 + (\boxed{h} - \boxed{c_i})^2 \end{cases}$$

Estimate target

Measured by IMU sensor

II. RSS + IMU Sensor Fusion



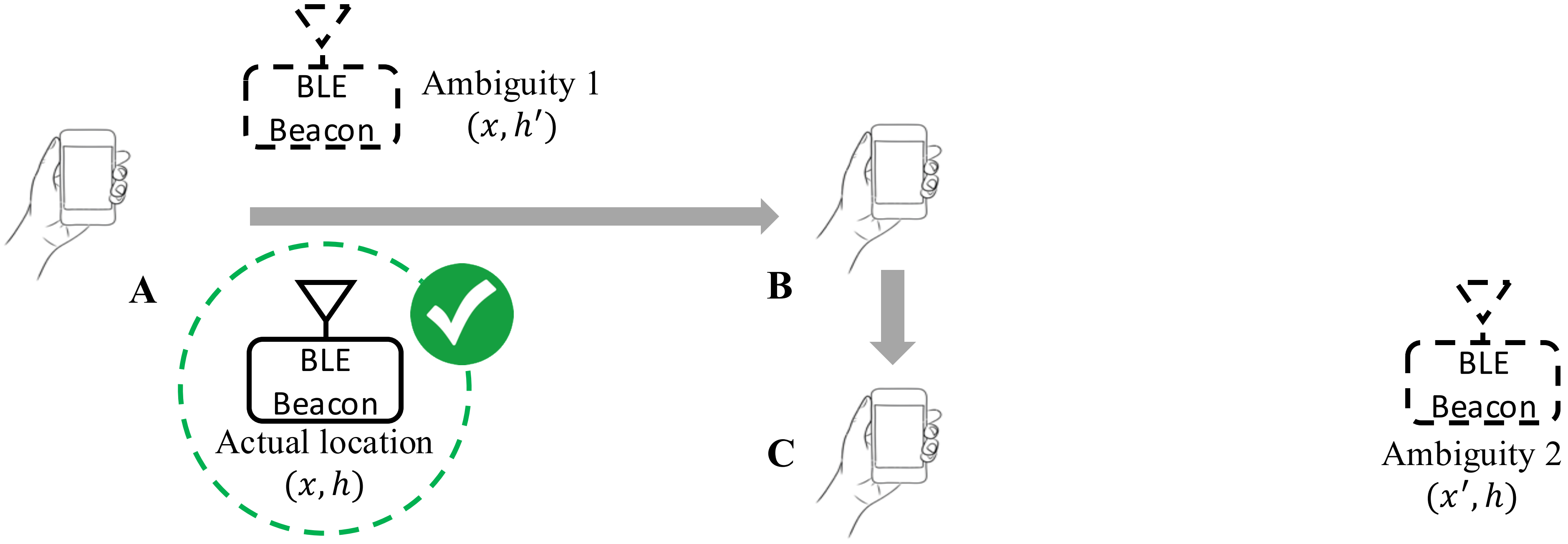


- Problem formulation: RSS reading + user's movement

$$\begin{cases} \mathrm{RS} = \Gamma(e) - 10n(e)\log(l_i) \\ l_i^2 = (x + \boxed{b_i} - \boxed{a_i})^2 + (h + \boxed{d_i} - \boxed{c_i})^2 \end{cases}$$

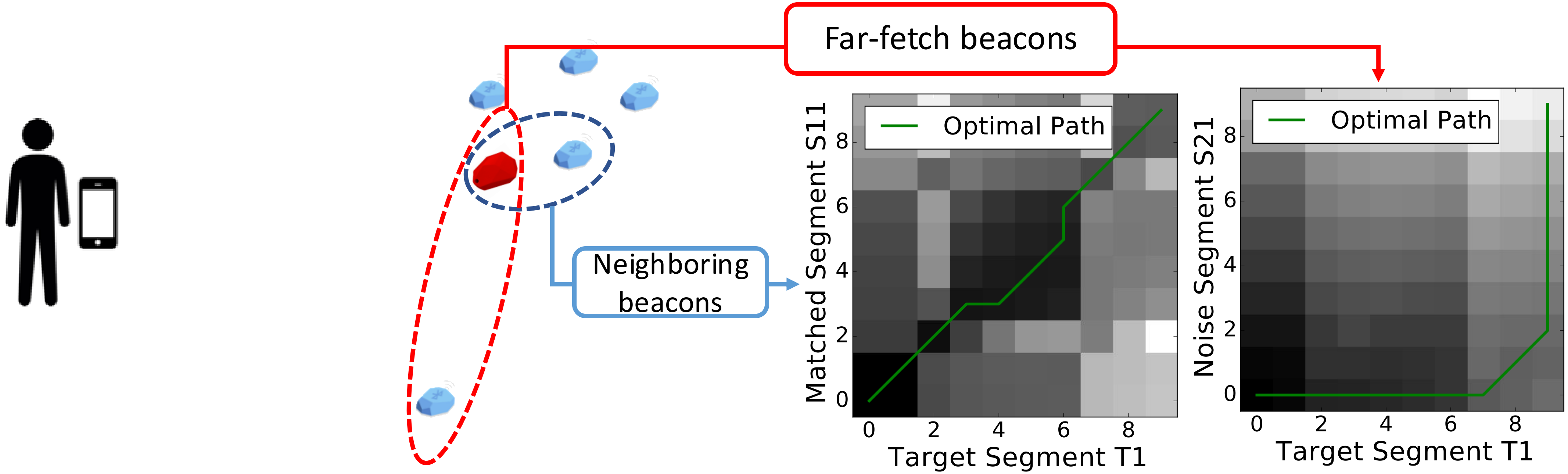
Measured by observer's/target's IMU sensor

II. RSS + IMU Sensor Fusion



- "**L-shaped**" movement process
  - Resolve ***symmetric*** issue
  - Accumulate enough data for sensor fusion

III. Clustering Algorithm



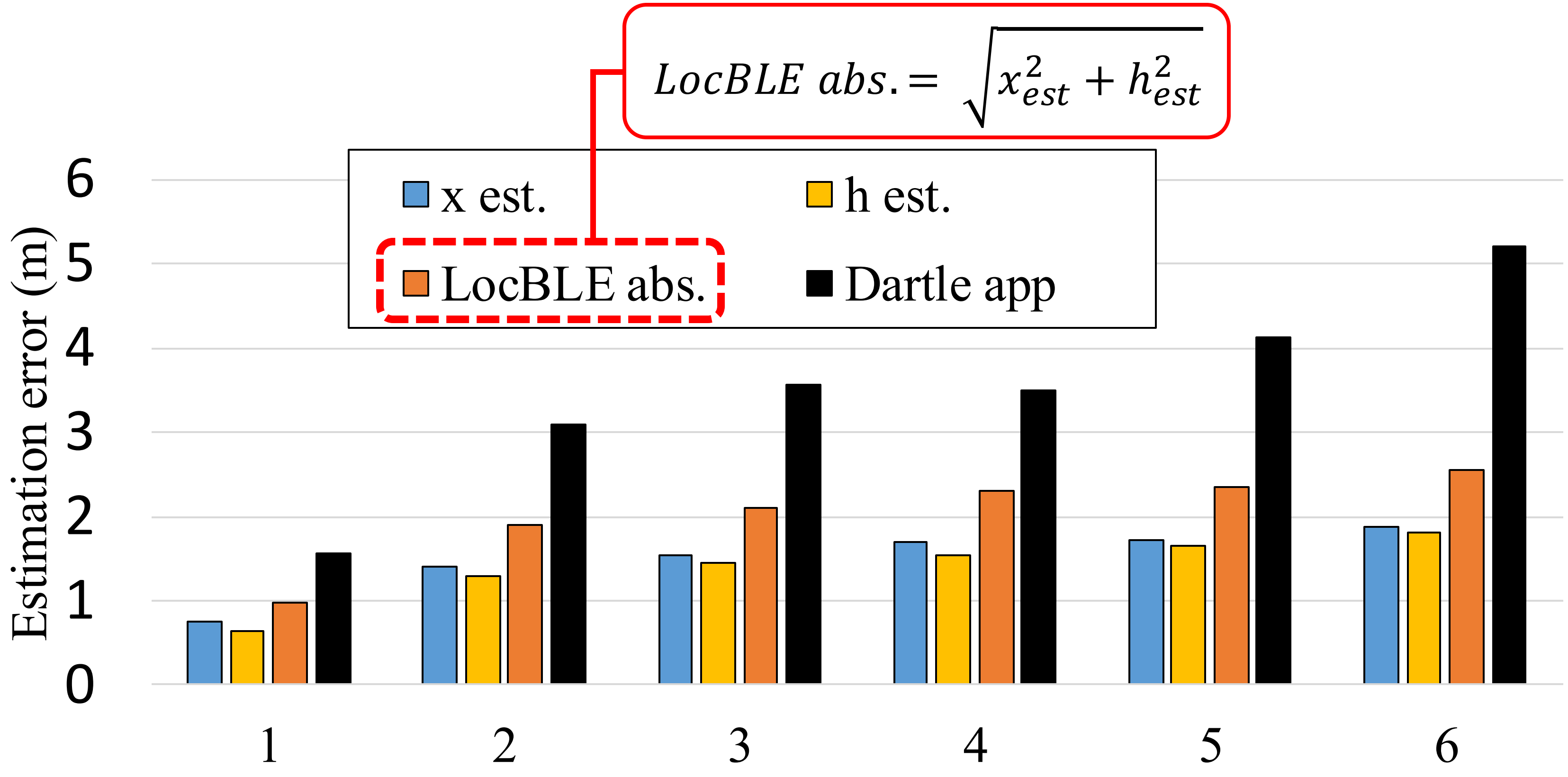
- Refine estimation results by leveraging neighboring beacons
- Clustering
  - Formulate cluster based on dynamic time warping (DTW) distance

Evaluation

Index	1	2	3	4	5	6	7	8	9
Image									
Name	Meeting room	Hallway	Bedroom	Living room	Restaurant	Store	Labs	Hall	Parking lot
Scale	5×5 (m^2)	8×3 (m^2)	7×7 (m^2)	7×7 (m^2)	9×10 (m^2)	9×10 (m^2)	8×10 (m^2)	9×11 (m^2)	16×15 (m^2)
Acc. (m)	0.8 ± 0.2	1.4 ± 0.3	1.4 ± 0.4	1.6 ± 0.3	1.6 ± 0.4	1.8 ± 0.6	2.3 ± 0.5	2.1 ± 0.5	1.2 ± 0.5

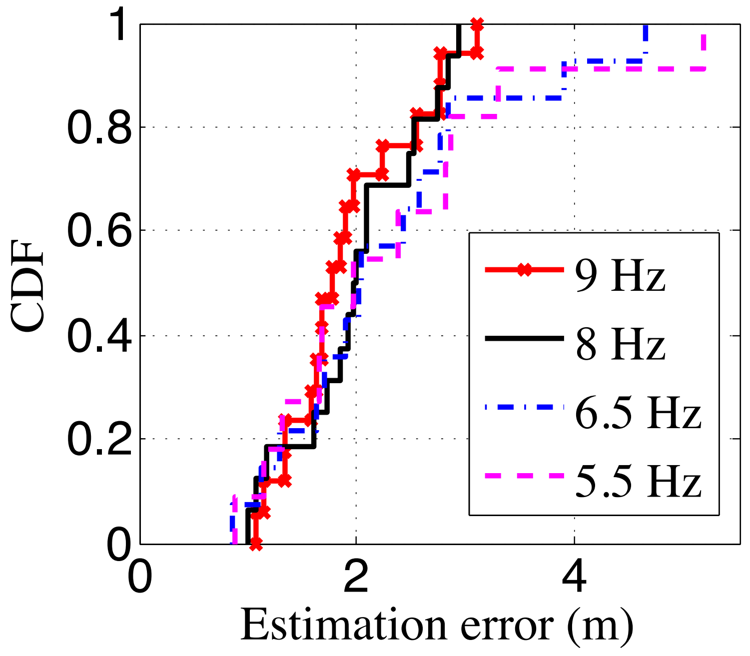
- Implementation:
  - LocBLE on both Android and iOS platforms
  - Tested on iBeacon protocol
  - **9** experimental environments

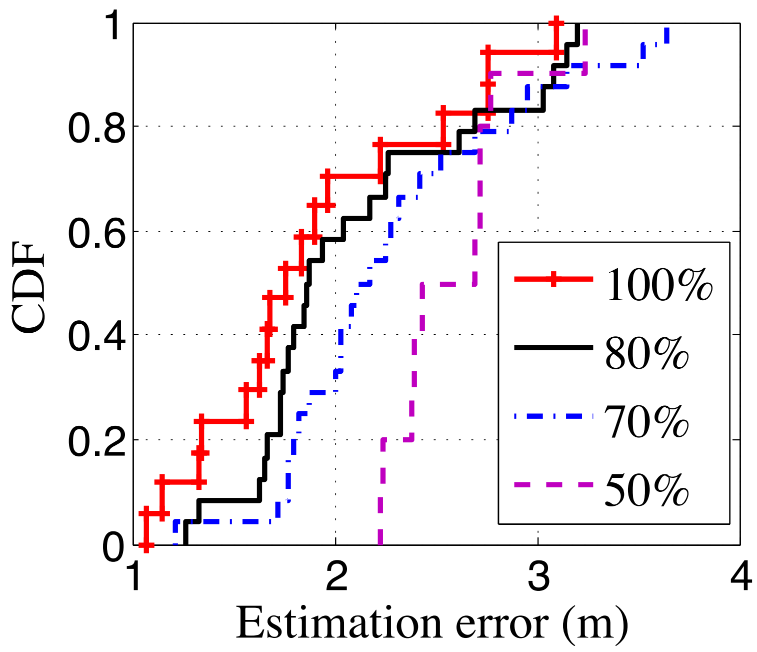
Evaluation



- Estimating stationary beacons' locations

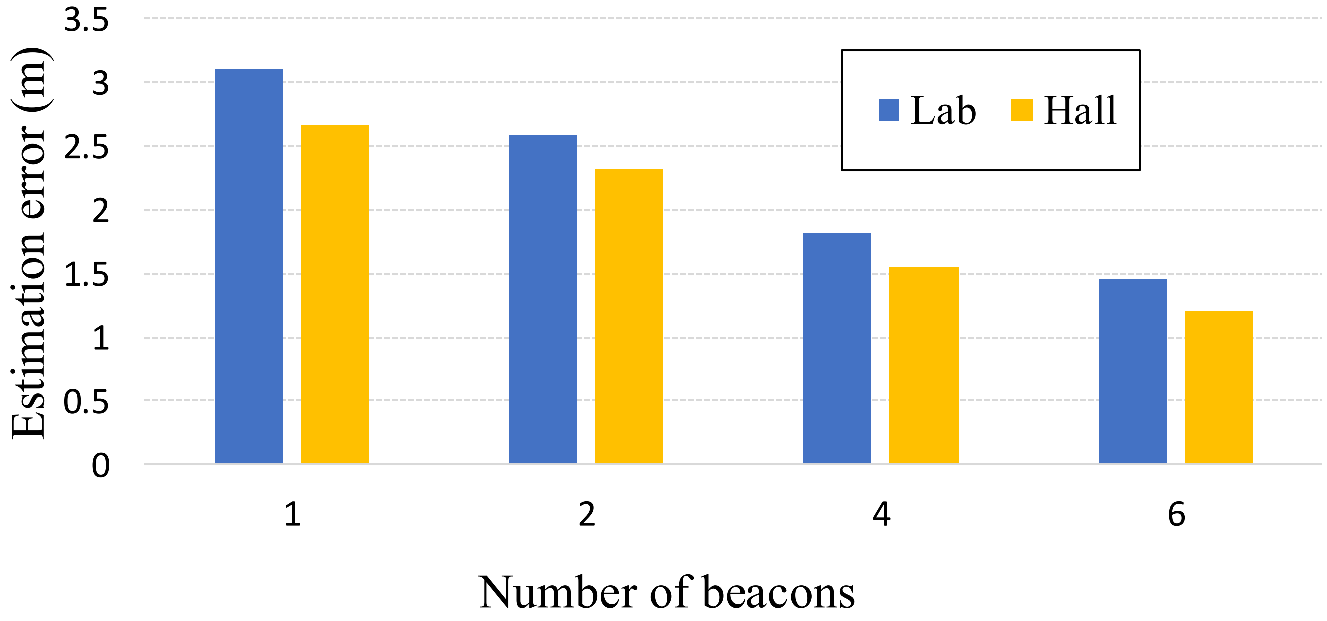
Evaluation





- Changing RSS sampling frequency
- Varying length of data trace for location estimation

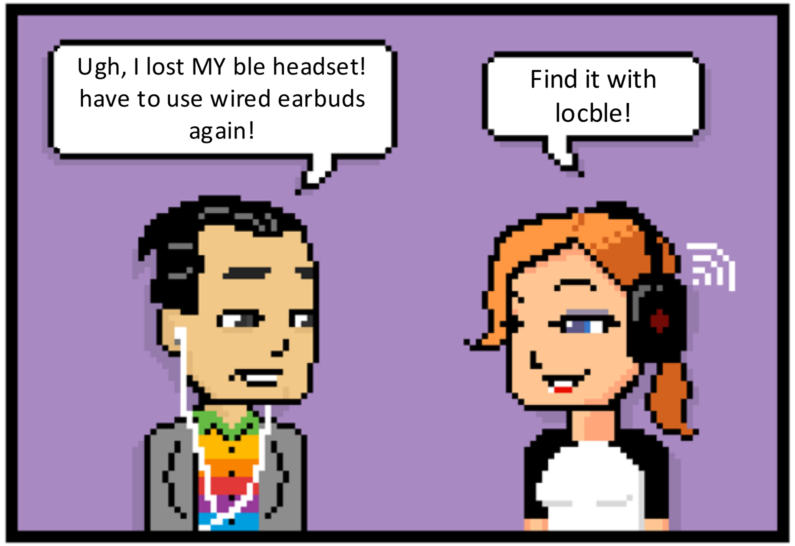
Evaluation



- Clustering Performance: estimations from neighboring devices **mitigate** the impact of noisy RSS readings


9:41 AM
List of BLE Devices
Add
Estimote 1
unknown
Estimote 2
unknown
Estimote 3
unknown
Estimote 4
unknown
Estimote 5
unknown
Selected Beacon
Relative Location
Environment
Line of Sight
Press 'Start Measure' to Measure
Label
Measure
Navigation
STOP

Conclusion



Comic credit: Rich Stevens @ imore.com

- Smartphone-based application for estimating location of nearby commodity BLE beacons
- 3 key components for extracting location information
  - RSS signal preprocessing
  - RSS + IMU sensor fusion
  - Clustering
- Achieved ~2 m localization accuracy in various environment

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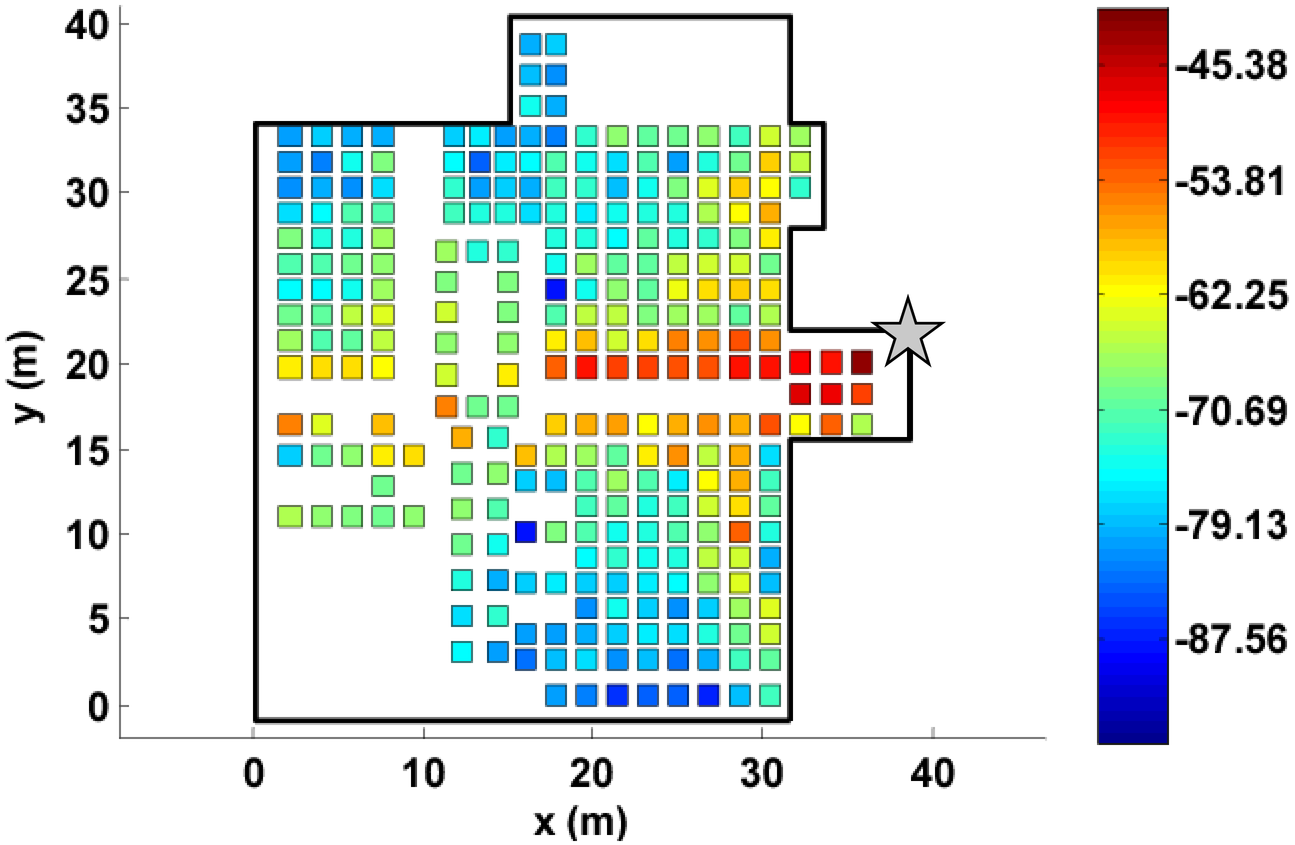
  - RSSI ranging
  - Fingerprinting
  - Ultra-wideband
  - Other techniques

Fingerprinting overview

- At setup time, for many locations throughout building
  - Measure signal strength to Network Access Point
- At run time, for the device that wants a location
  - Measure signal strength to Access Point
  - Look up measurement in database to get location



Fingerprinting improvements

- Measurements can use several Access Points simultaneously
  - Improves accuracy quite a bit

- We can use many existing resources
  - Cellular networks can do fingerprinting
  - Deploy your own BLE beacons throughout environment

Fingerprinting challenges

- Effort to create database in the first place
- Environment is not stable
  - Signal strength changes as chairs, doors, and people move
- Measurements vary between devices
  - Differ based on antennas, cases, how you hold it, etc.

State-of-the-art: median accuracy of 0.5-1.5 meters

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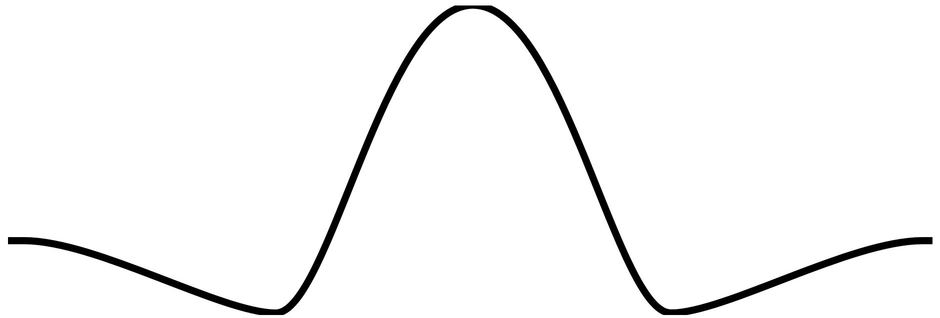
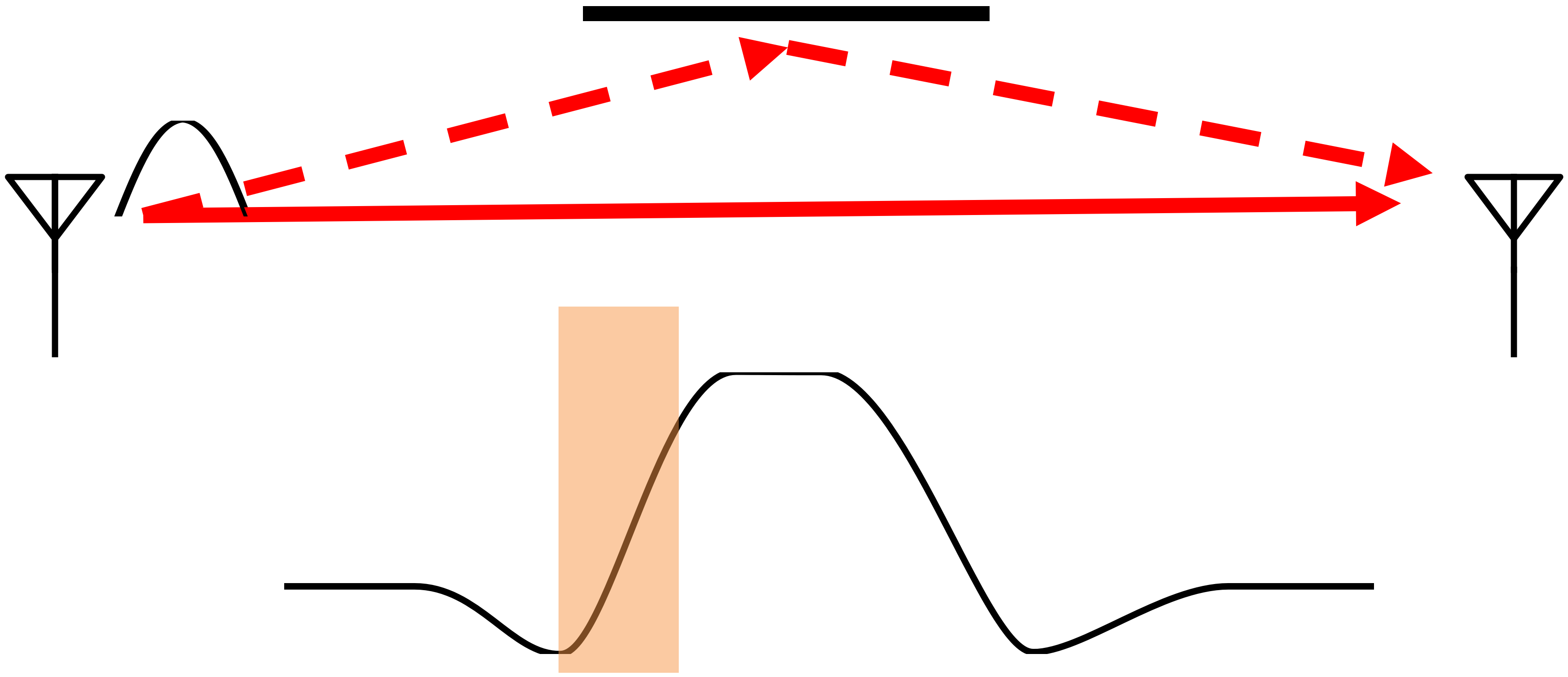
Improving accuracy

- To get high accuracy, let's return to trilateration
- Plan: Send an RF signal from one device and time how long it takes to reach another
  - Brief transmissions rather than continuous ones like GNSS
- Problem: When does this signal arrive?
  - Need to measure the "arrival time" accurately



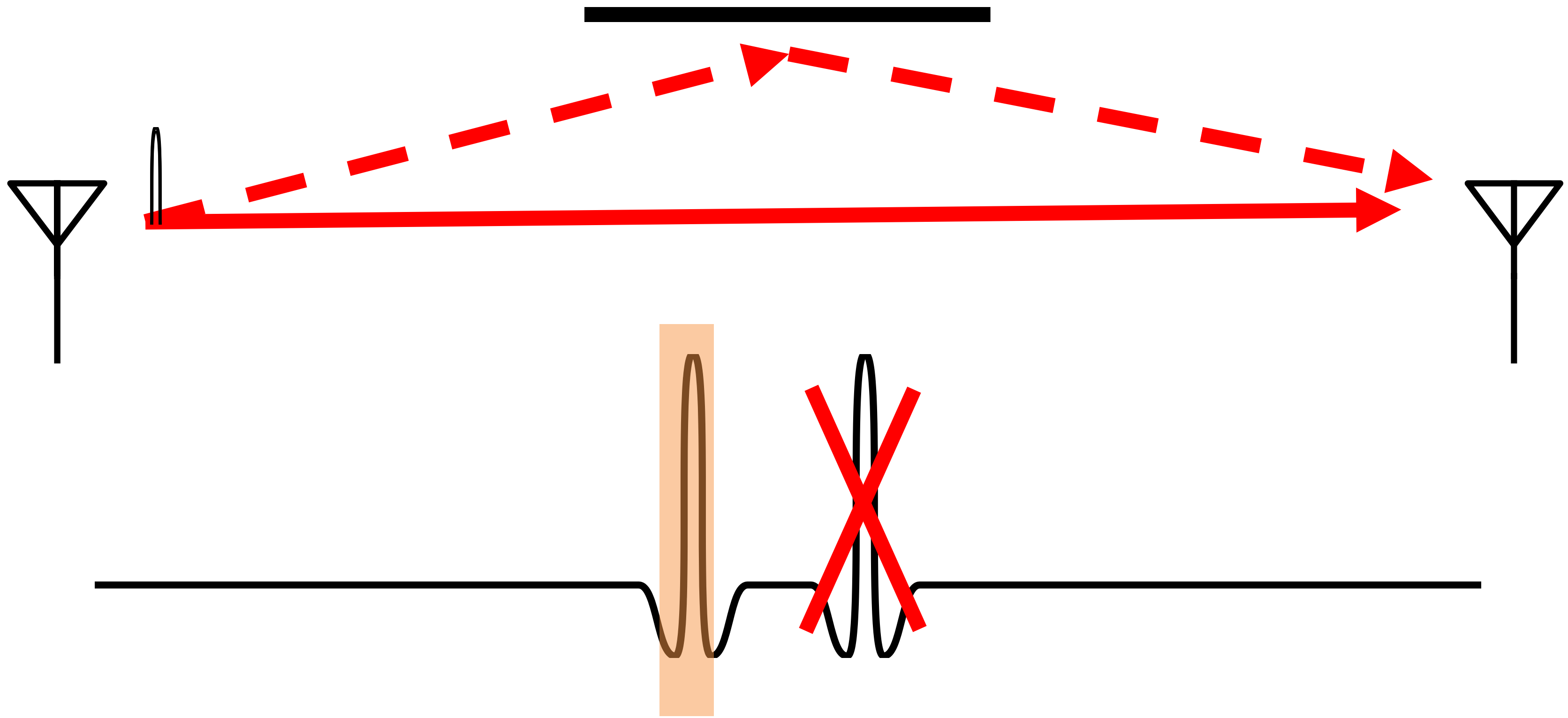
Multipath problem

- Real-world signals bounce off of things in the environment
  - Multiple, time-delayed versions of signal arrive at antenna
  - Result smears out the arrival of energy in time
    - More reflections mean more peak energy, but longer rise time
  - This **<u>isn't predictable</u>**. Depends on the exact environment configuration



Why does ultra-wideband yield better localization performance?

- Wider bandwidth makes the RF pulse narrower in time
  - Make it narrow enough, and multipath **becomes entirely separate**

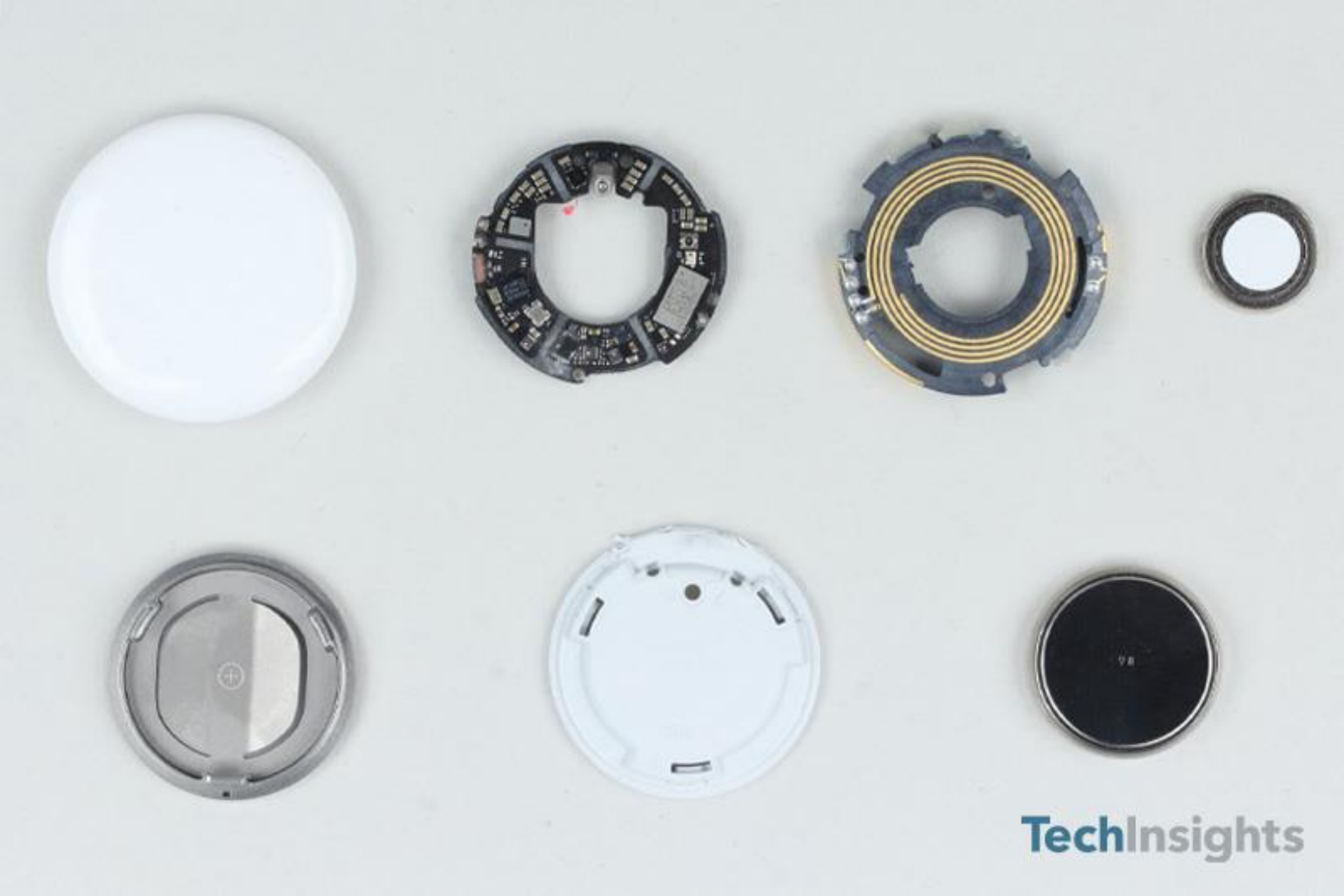


Ultra-wideband localization system

- Narrow ultra-wideband pulses makes arrival timing easier

- The rest is a copy of well-known techniques
  - Deploy anchors in the environment with known positions
  - Measure distance between anchors and device
    - Time of Flight (if anchors transmit)
    - Time Difference of Arrival (if devices transmit)
  - Trilateration to find position

Ultra-wideband localization system



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Ultrasound

- Advantages
  - Solves the barrier problem
    - Human spaces already designed to contain sound
  - Easier to get high-accuracy results
    - Sound is ~1,000,000x slower than light
    - **Less synchronization is needed** to get same accuracy
- Disadvantages
  - More energy to transmit
  - Slower update rate (still sub-second)
  - Limited range
  - Pets can hear it

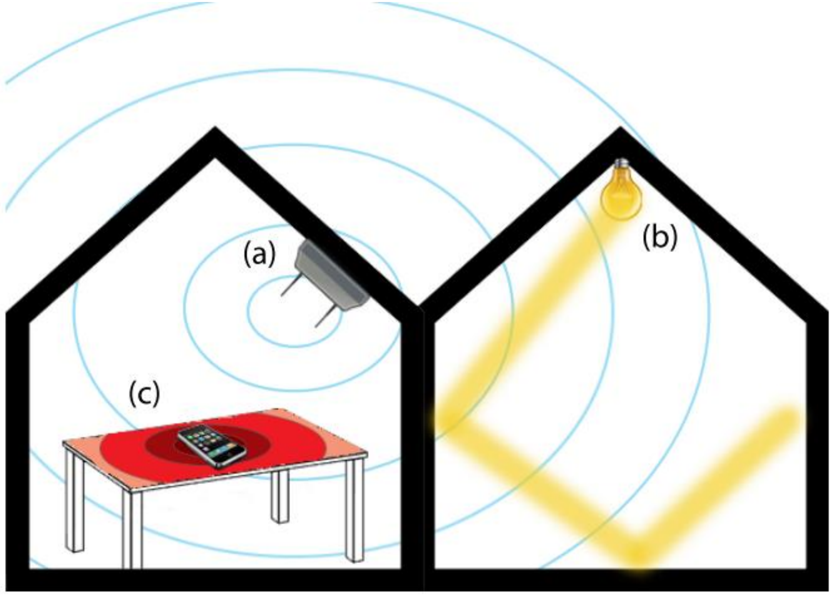
ARKit (and other AR techniques)

- Leverage smartphone cameras for positioning
  - Pictures of a user's surroundings can be compared to floorplan
  - Related to SLAM techniques (Simultaneous Localization And Mapping)

- Can build an incredibly accurate system
  - With a bit of bootstrapping
  - Probably applies most to robotics use cases

Vibrations

- Determine shared context of a table
  - Vibratory motors and IMUs are common
  - Signaling demonstrates nearby devices



(a) Establishing a first-time Bluetooth connection

(b) Desktop detection for pre-connected devices

(c) Connecting with hidden table-level services

(d) Establishing a desktop area network

RF Antenna Array + AoA

- Antenna arrays can be used to determine the angle of an incoming signal
  - Allows the use of normal RF communication (WiFi or BLE)

- BLE 5.1 includes AoA localization