ArrayTrack: A Fine-Grained Indoor Location System

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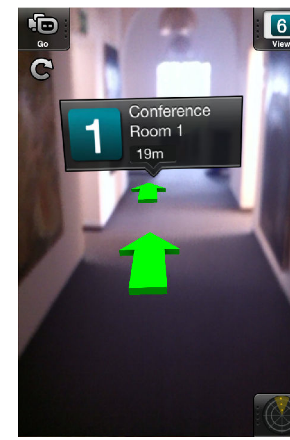
Precise location systems are important

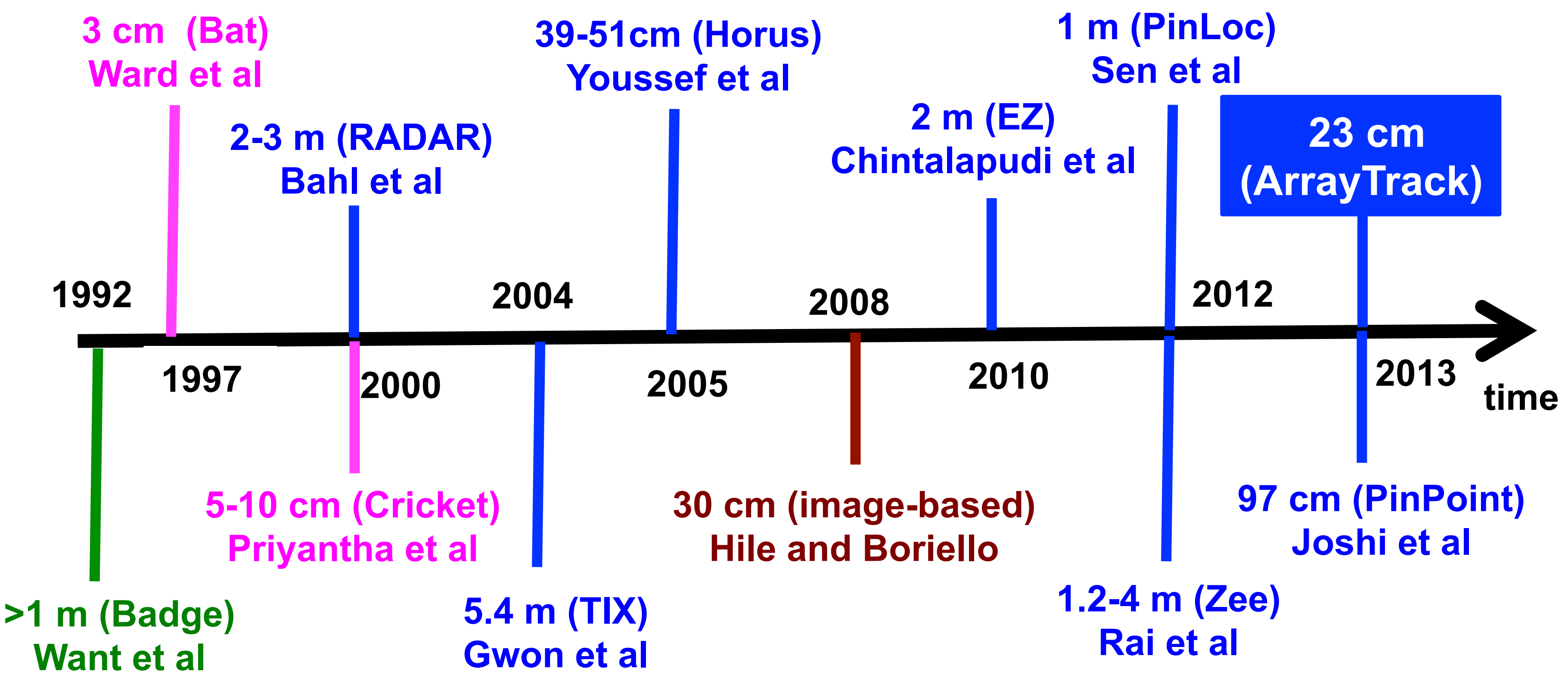
- Outdoors: **GPS**
  - Accurate for navigation (meters)
  - Signals fade in indoor environments

- Precise and rapid indoor location enables:
  - Augmented reality on the smartphone, wearable or glasses
  - Fine-grained location in supermarkets, libraries or museums
  - Controlling network access based on desk or room



- Known technologies: **not accurate enough (WiFi), require dedicated infrastructure (ultrasound) or require cameras and good light conditions (vision)**

Timeline of indoor location systems



Two observations about WiFi

1. **Increasing number of antennas on an access point (AP)**
   - 802.11n MIMO links: improve capacity and coverage
   - Draft 802.11ac (2014): 8 MIMO spatial streams (8 antennas)

4 antennas

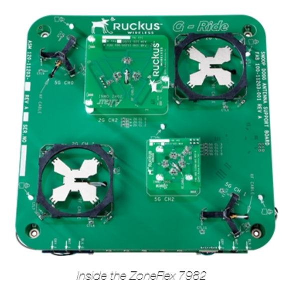
Cisco Aironet 3600

6 antennas

Motorola AP8132

Cisco Aironet 1250

14 antennas



RUCKUS ZoneFlex 7982

16 antennas

Xirrus XR7630

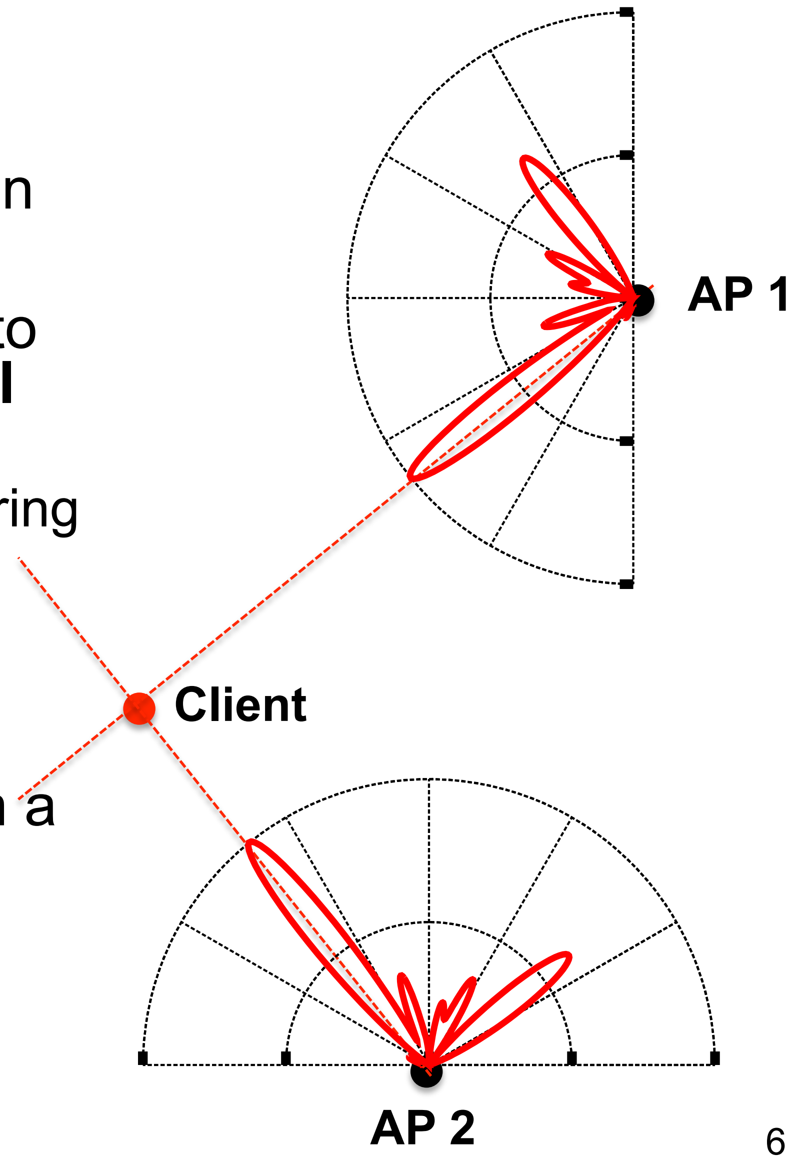
Two observations about WiFi

1. **Increasing number of antennas on an access point (AP)**
    - 802.11n MIMO links: improve capacity and coverage
    - Draft 802.11ac (2014): **eight** MIMO spatial streams

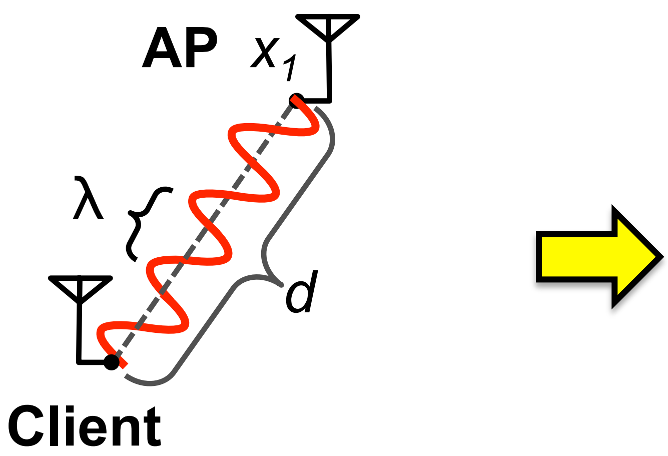
2. **WiFi is ubiquitous and densely deployed**
    - WiFi is now available on airplanes, subways and buses
    - APs density is ever-increasing in the urban environment

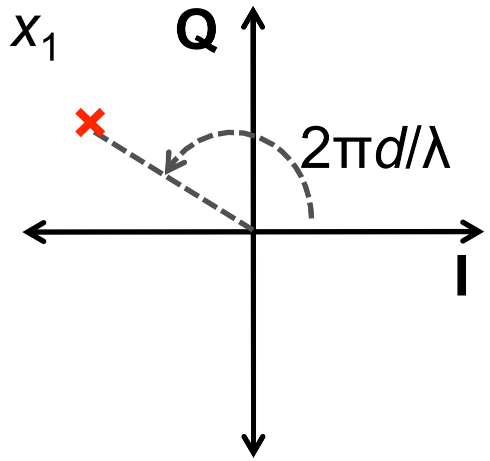
Our Approach

- AP overhears a client's transmission
- **AP** **leverages multiple antennas** to generate physical **angles of arrival (AoA)** of a client's signals:
  - ***AoA spectrum***: power versus bearing at one AP
- With multiple APs, central server **synthesizes** AoA spectra to obtain a location estimate for the client



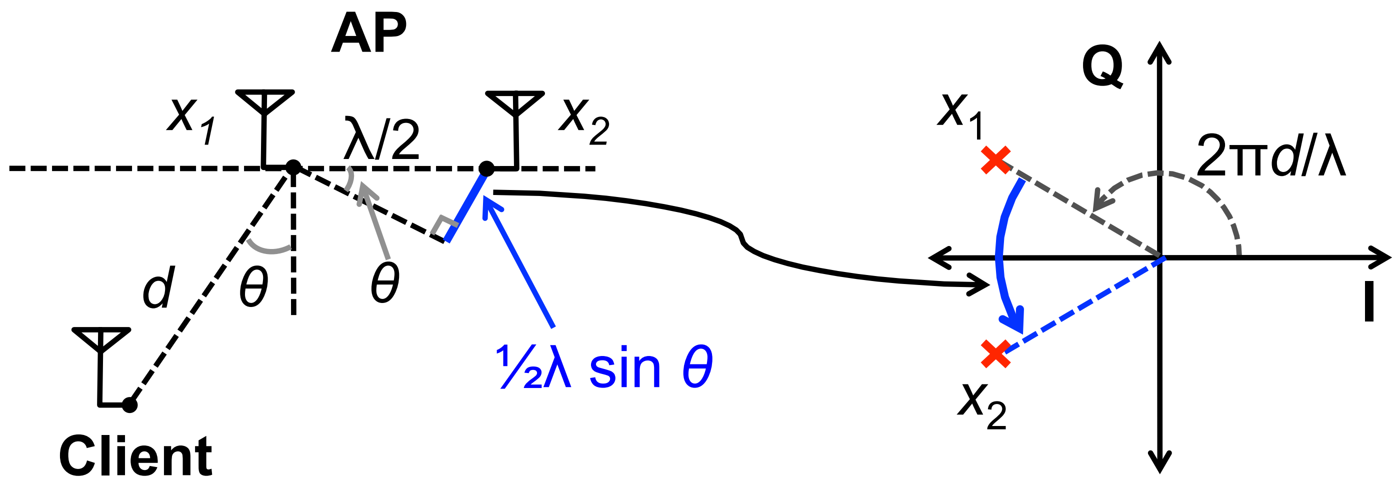
Basic theory of operation





Measured baseband signal at AP

Basic theory of operation

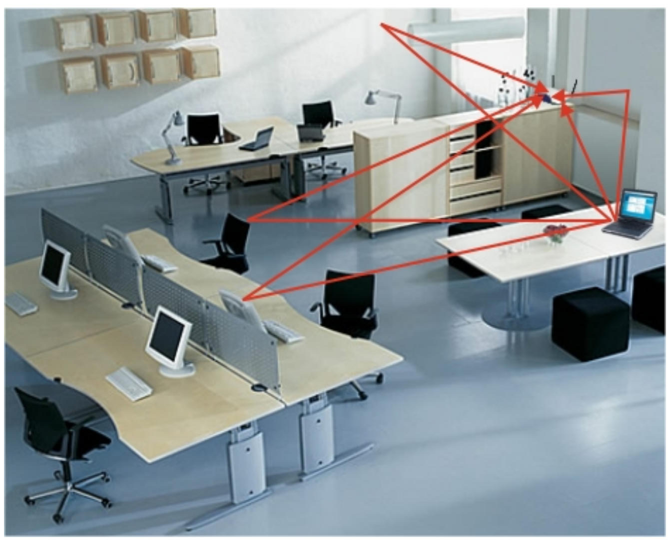


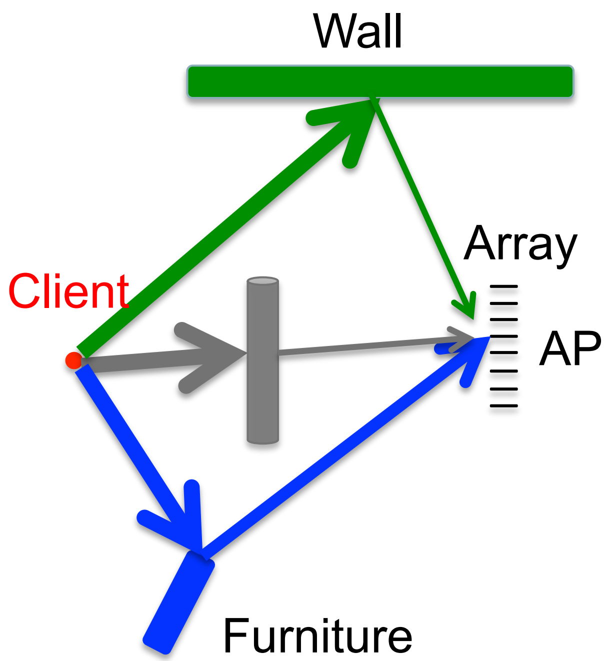
In a solely line-of-sight environment, phase measurements give client's bearing to AP *θ*

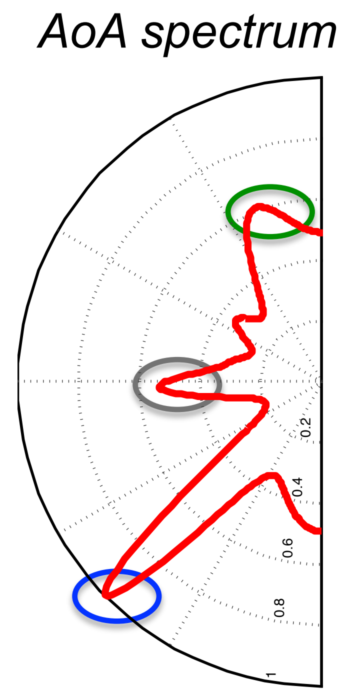
$$\theta = \arcsin\left(\frac{\angle x_2 - \angle x_1}{\pi}\right)$$

The challenge: multipath reflections

- **Problem #1:** Strong multipath reflections indoors
- **Problem #2:** **Direct path** attenuated or completely blocked
  - **Direct path signal may not be the strongest**

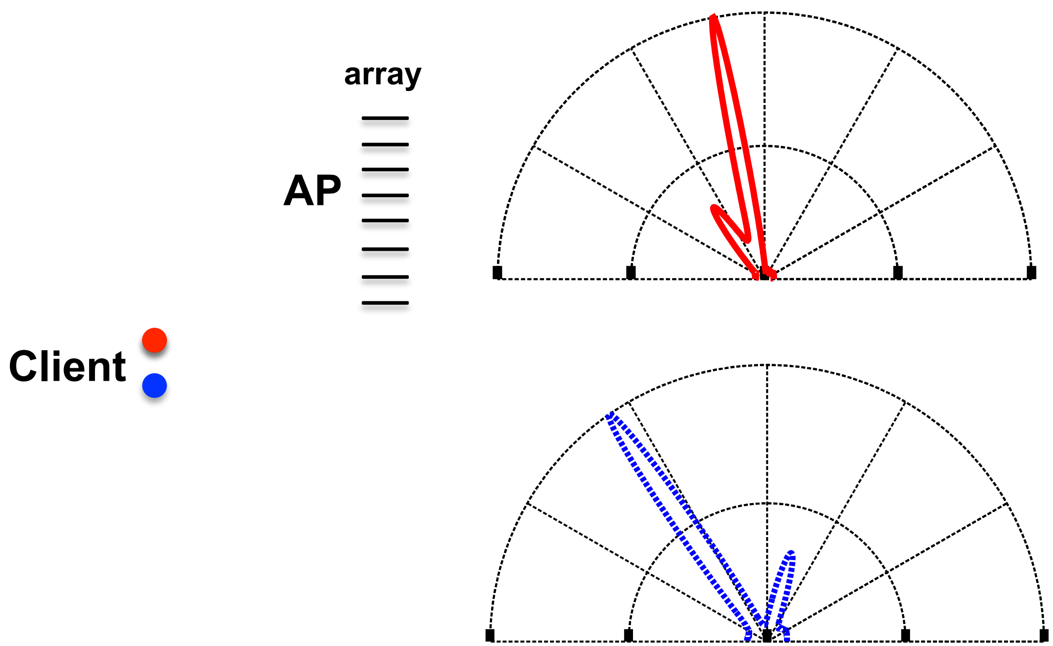






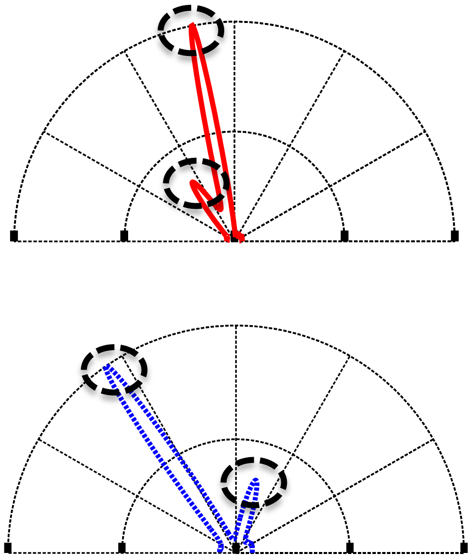
ArrayTrack's multipath suppression algorithm

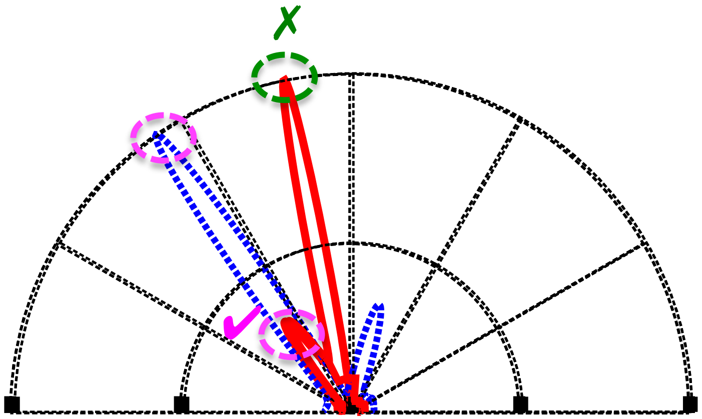
- **<u>Key observation</u>**: direct path bearing is more stable than reflection path bearings when client moves slightly



ArrayTrack's multipath suppression algorithm

1. Given: AoA spectra from two nearby locations
2. Find the peak bearings in each AoA spectrum
3. Discard any peak not paired with a peak in the other AoA spectrum



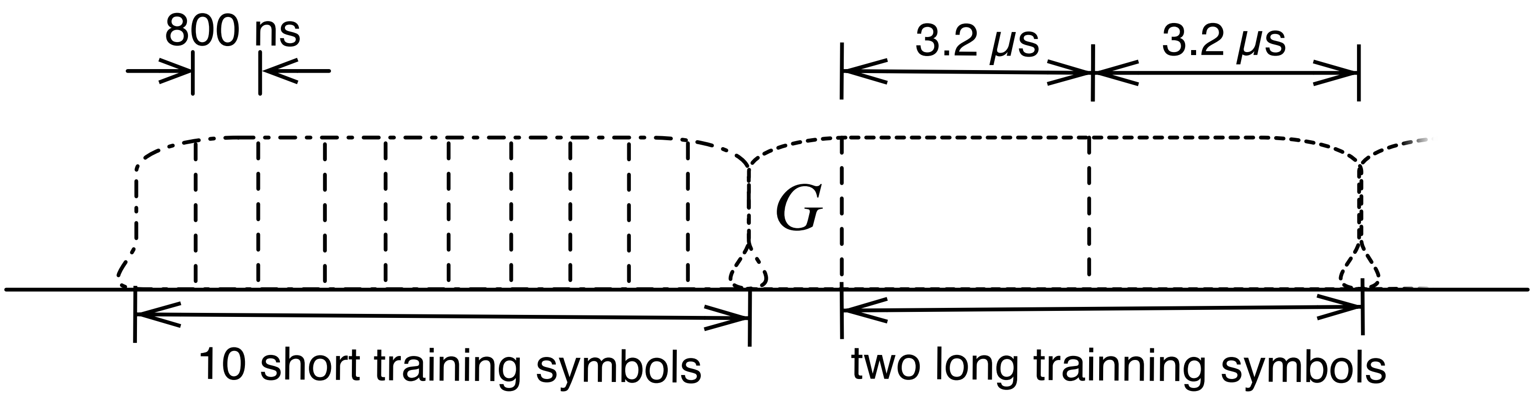


Two peak bearings within five degrees are considered ***paired***

Step 1: detection and recording

- Content of packet and modulation type do not matter

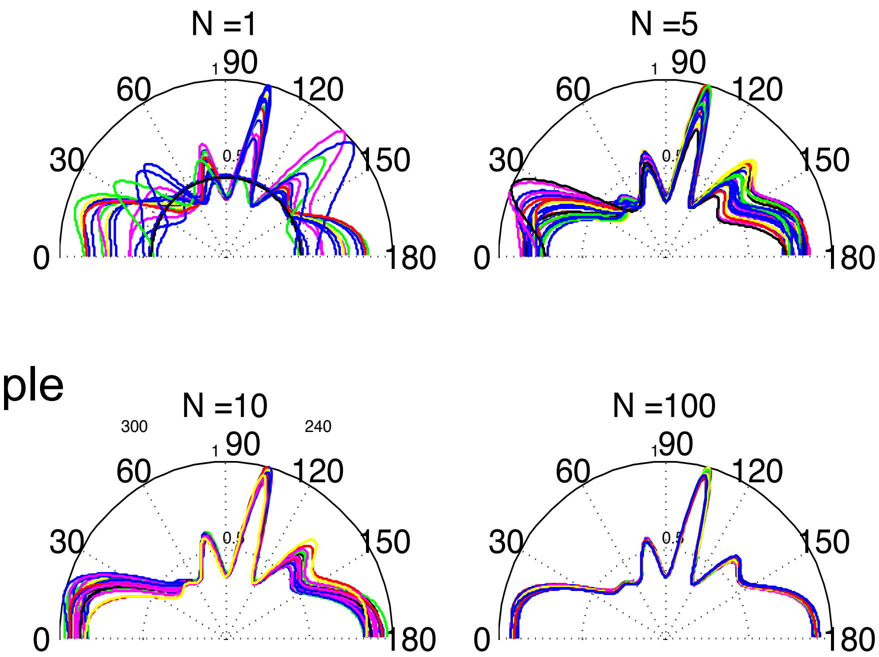
- Works with any part of a packet
  - ArrayTrack utilizes the most robust **preamble part**



Preamble

Step 1: detection and recording

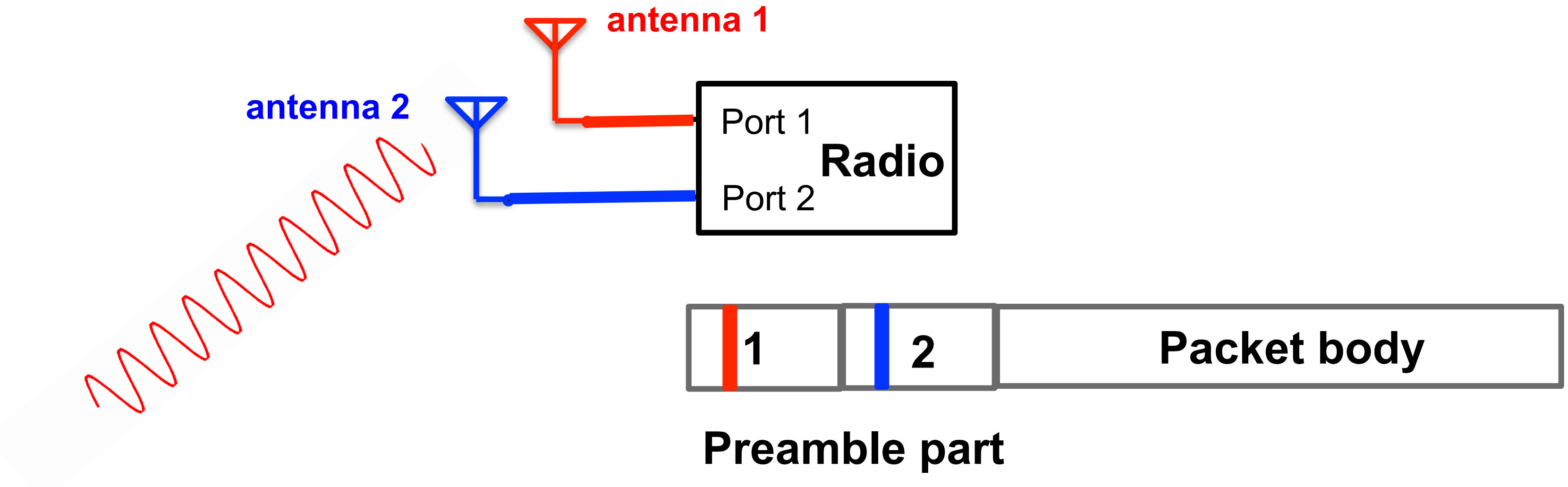
- Very small part of a packet needed
  - For a 40 MHz sampling rate, one sample is **25 ns**
  - In the absence of noise, one sample works
  - Employ **multiple** samples for averaging to remove noise



Preamble part

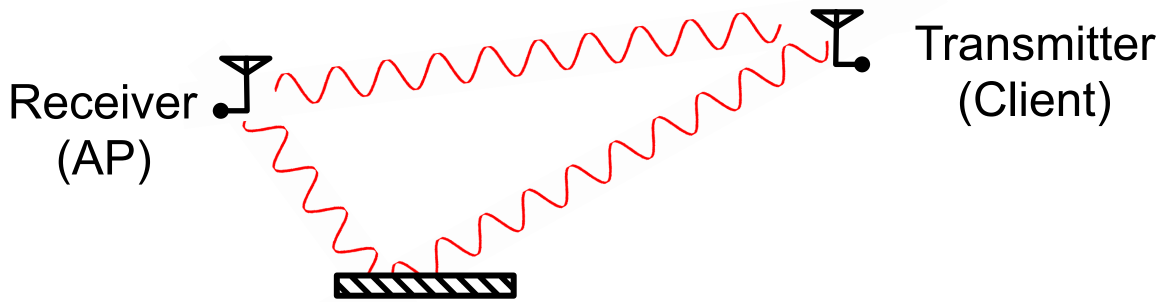
Step 1: detection and recording

- **Diversity synthesis:** existing 802.11 radios record the 1st half of the preamble from antenna 1 and the 2nd half from antenna 2
- **ArrayTrack's diversity synthesis algorithm**
  - Record 10 samples from the first preamble half and another 10 samples from the second preamble half with different antennas
  - Double the number of antennas we can utilize for ArrayTrack

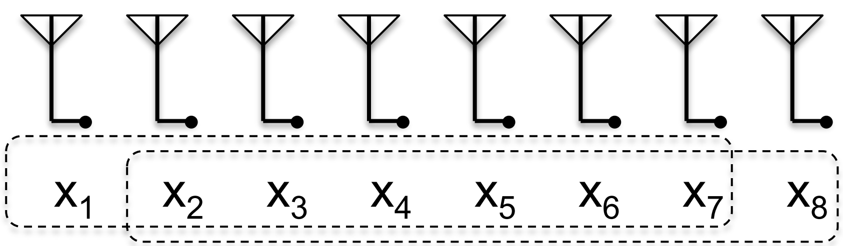


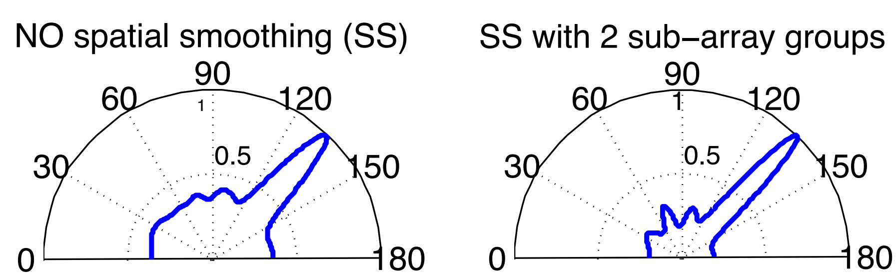
Step 2: AoA spectrum generation

- MUSIC algorithm [Schmidt, 1986] for AoA spectrum estimation
  - Does not work well for indoor environment because of ***coherent signals:***



- Spatial smoothing (SS) [Shan et al, 1985] handles coherent signals

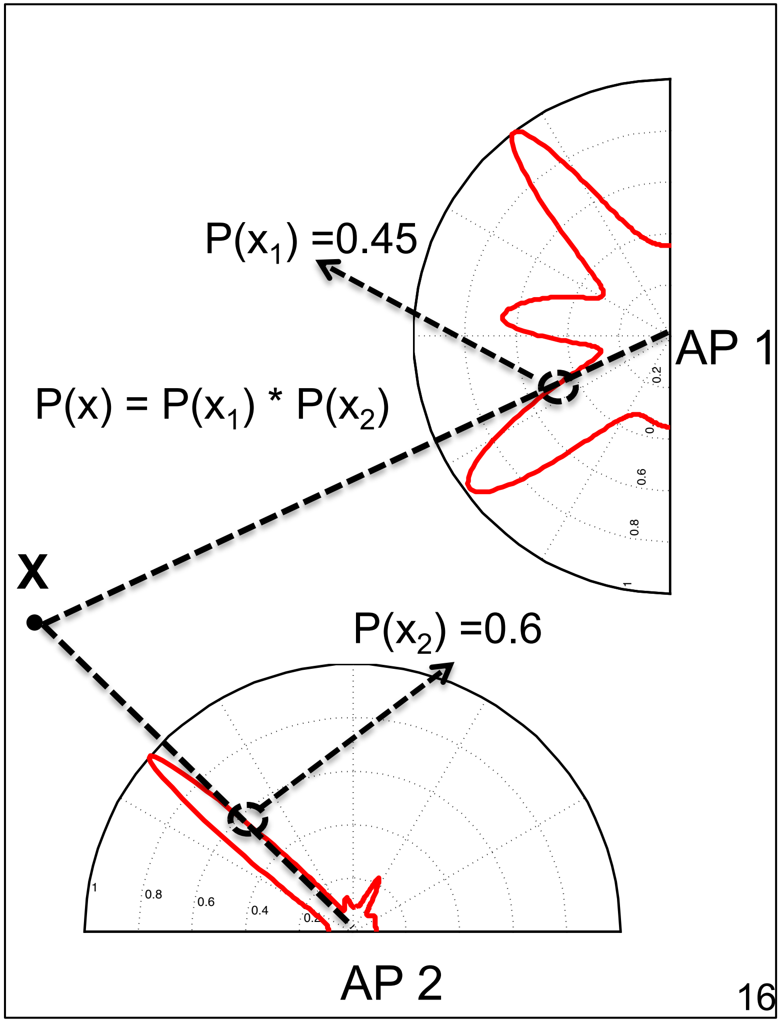




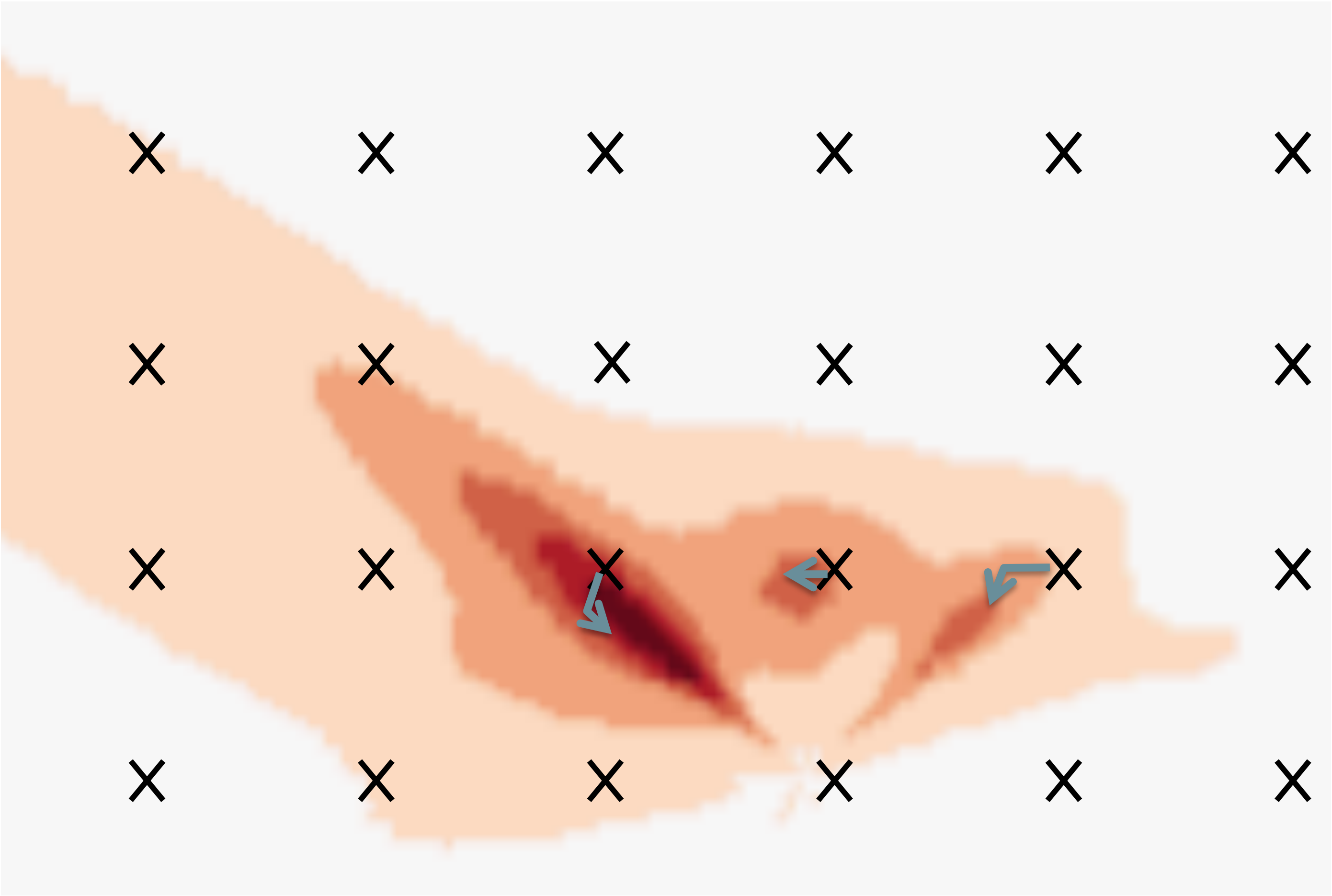
Step 3: AoA spectra synthesis

- N APs generate N AoA spectra

- For a random position **X**,
  the likelihood of being at **X**
  is a multiplication of
  probabilities from multiple APs

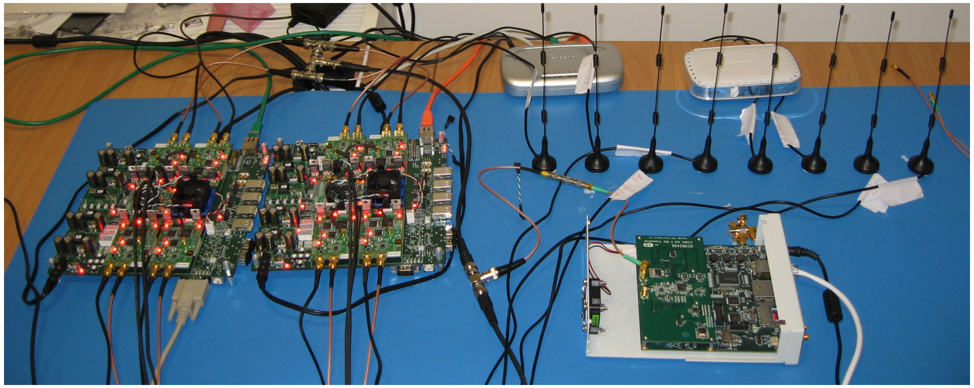


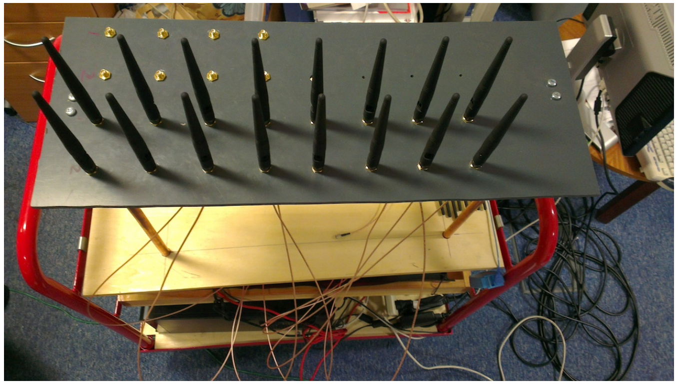
Step 4: search for highest probability position



Implementation

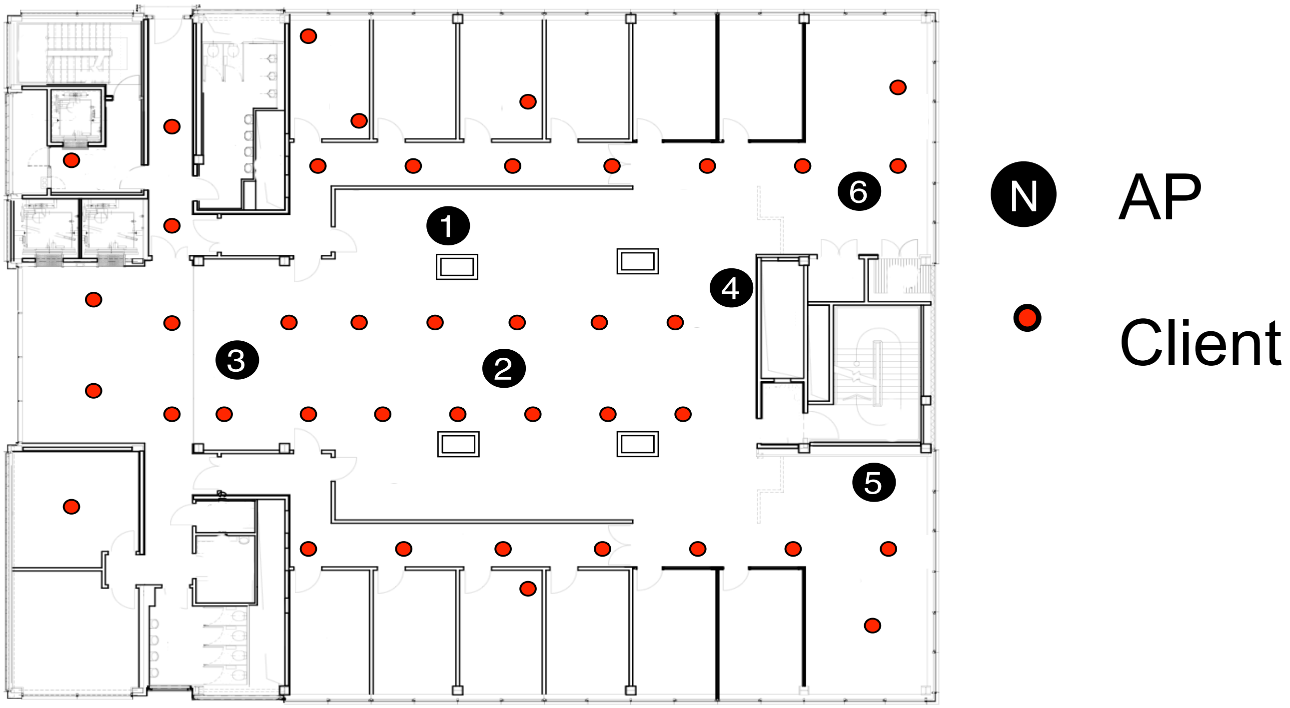
- **AP:** two WARPs, each with four radio boards (eight antennas)
  - Custom FPGA design using Xilinx System Generator for packet synchronization, diversity synthesis, RF oscillator synchronization
  - 4-16 antennas placed in a linear arrangement, spaced at λ/2 (6.13 cm)
- **Clients:** Soekris boxes equipped with 802.11 radios
- **Backend location server:** implemented in Matlab (1,000+ LoC)





Floorplan: client and AP positions

- Backend server has knowledge of each AP's location



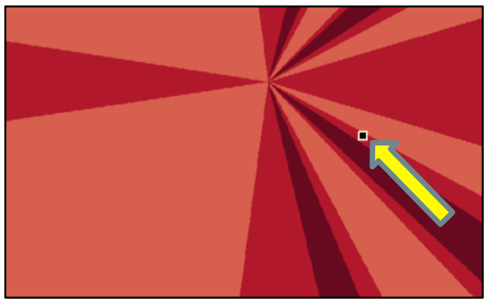
Evaluation

- **How accurate is MUSIC + SS?**
- ArrayTrack's multipath suppression improvement
- Effect of number of antennas on each AP
- Effect of client-AP differences in height

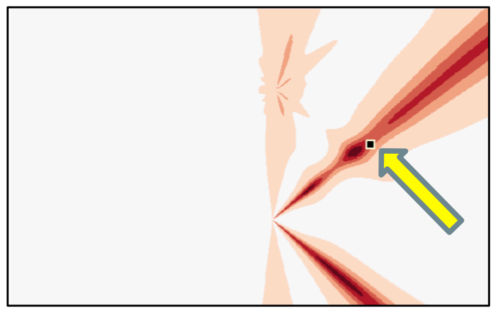
Effects of number of APs

- Heatmap example of increasing number of APs

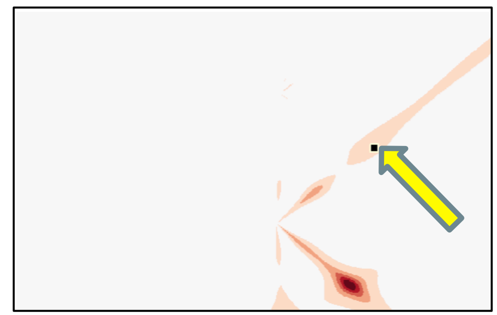
one AP



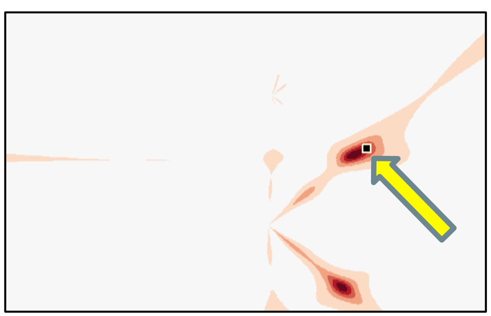
two APs



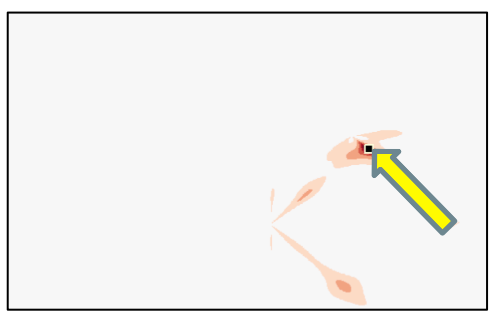
three APs



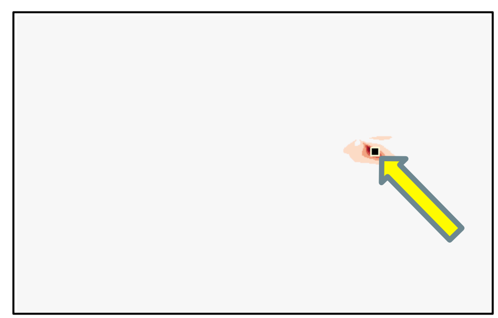
four APs



five APs

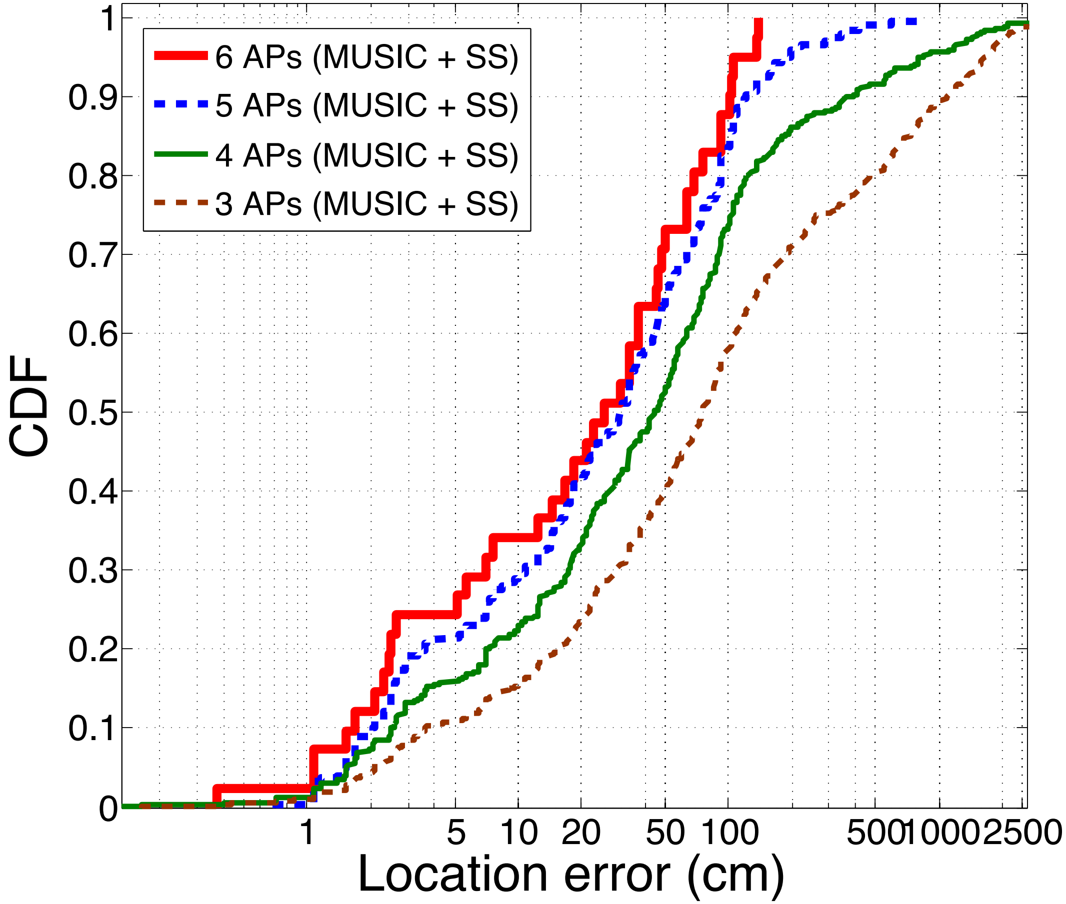


six APs



MUSIC + SS achieves 26 cm accuracy

- In general, with increasing number of APs, more accurate location information can be obtained

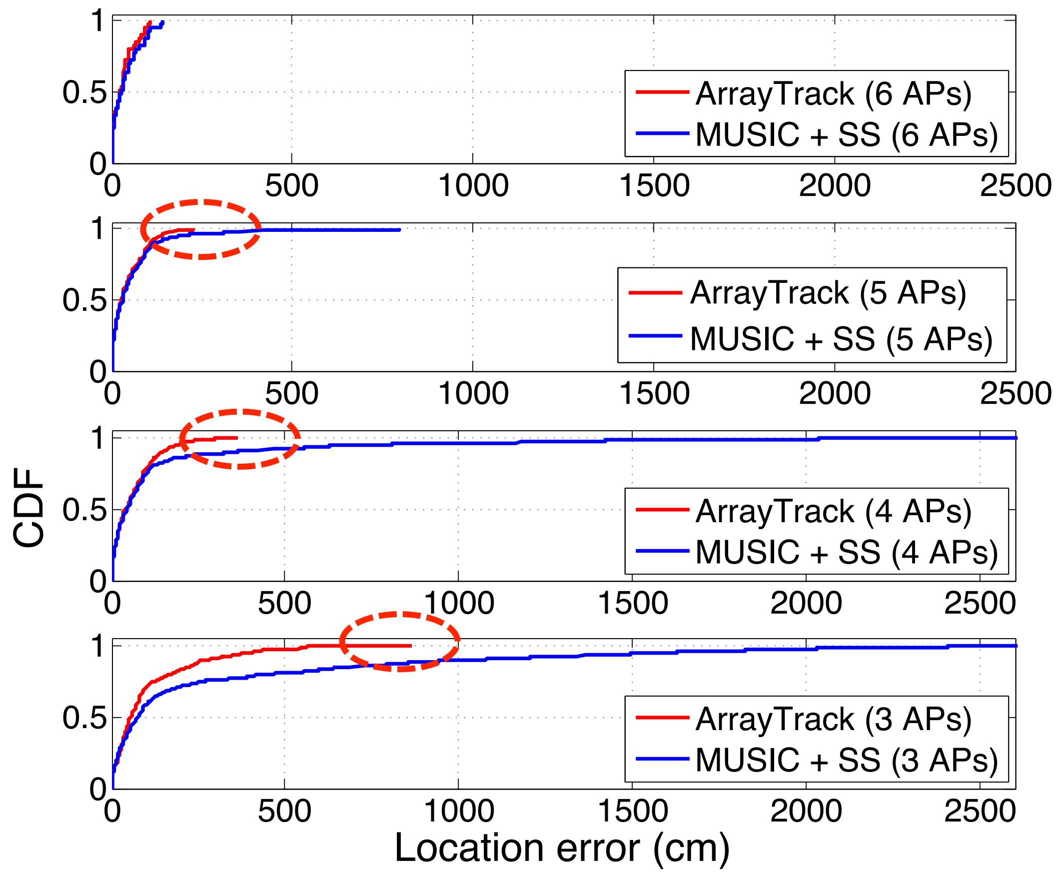


Evaluation

- How accurate is MUSIC + SS?
- **ArrayTrack's multipath suppression improvement**
- Effect of number of antennas on each AP
- Effect of client-AP differences in height

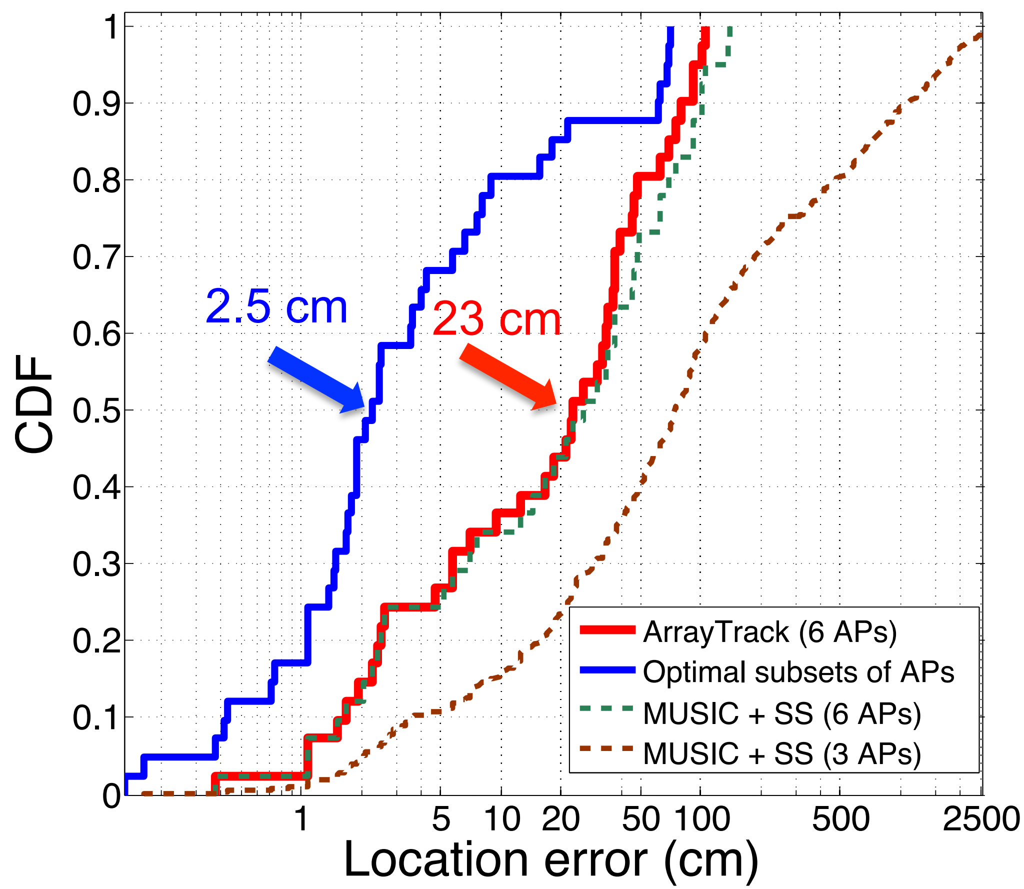
Multipath suppression improves accuracy

- Median: 23 cm (ArrayTrack with 6 APs)
- With multipath suppression, the long tail is removed
- The fewer APs, the more important is multipath suppression



Optimal subset of APs

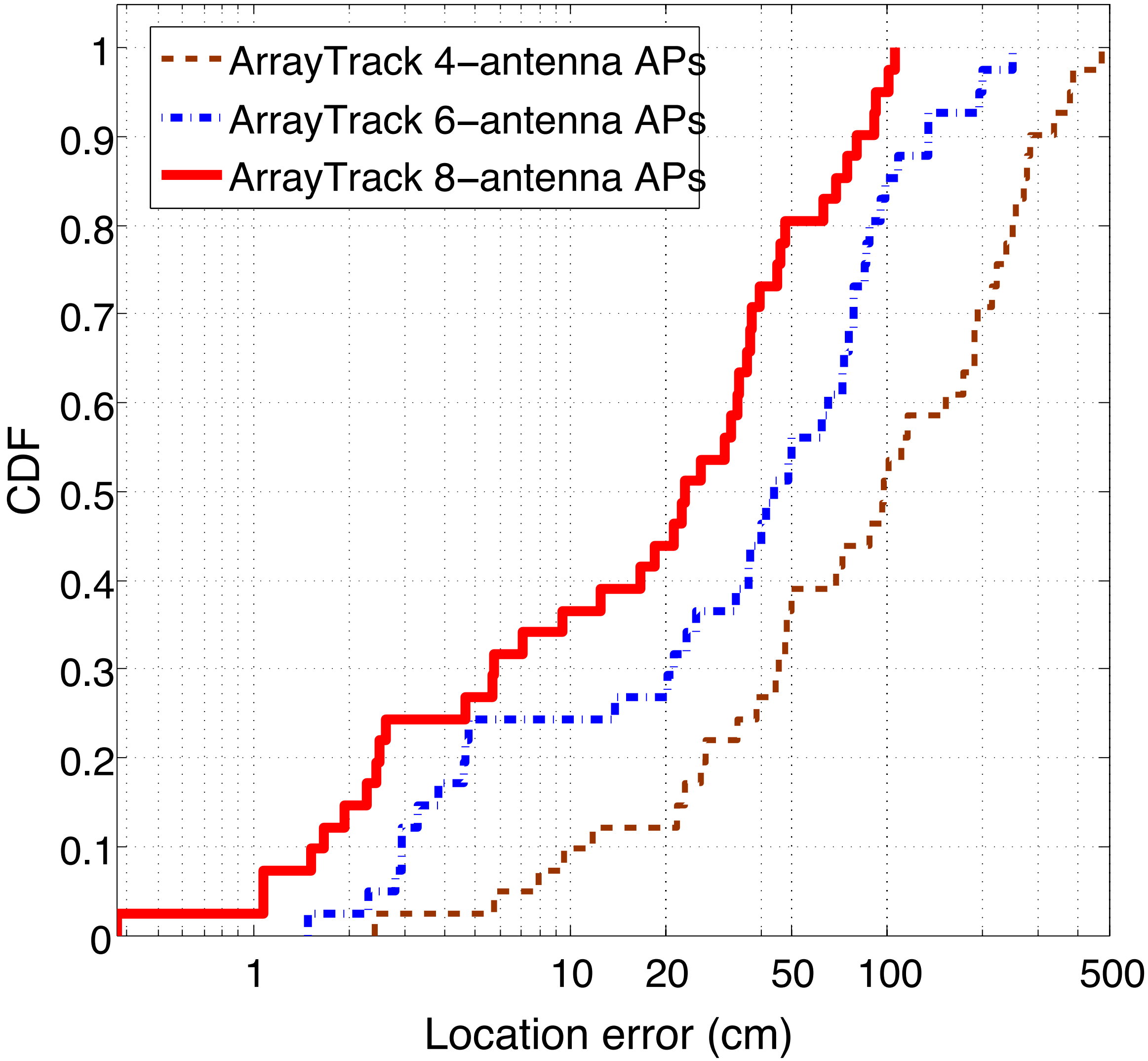
- On average, 6 APs present the best result
- It's not true for a particular position



Evaluation

- Effect of number of APs on accuracy
- Multipath suppression improvement
- **Effect of number of antennas on each AP**
- Effect of client-AP differences in height/orientation

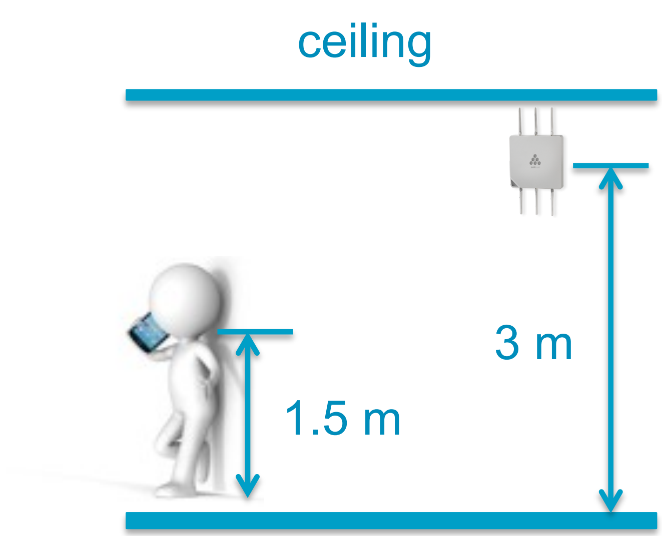
Number of antennas at AP

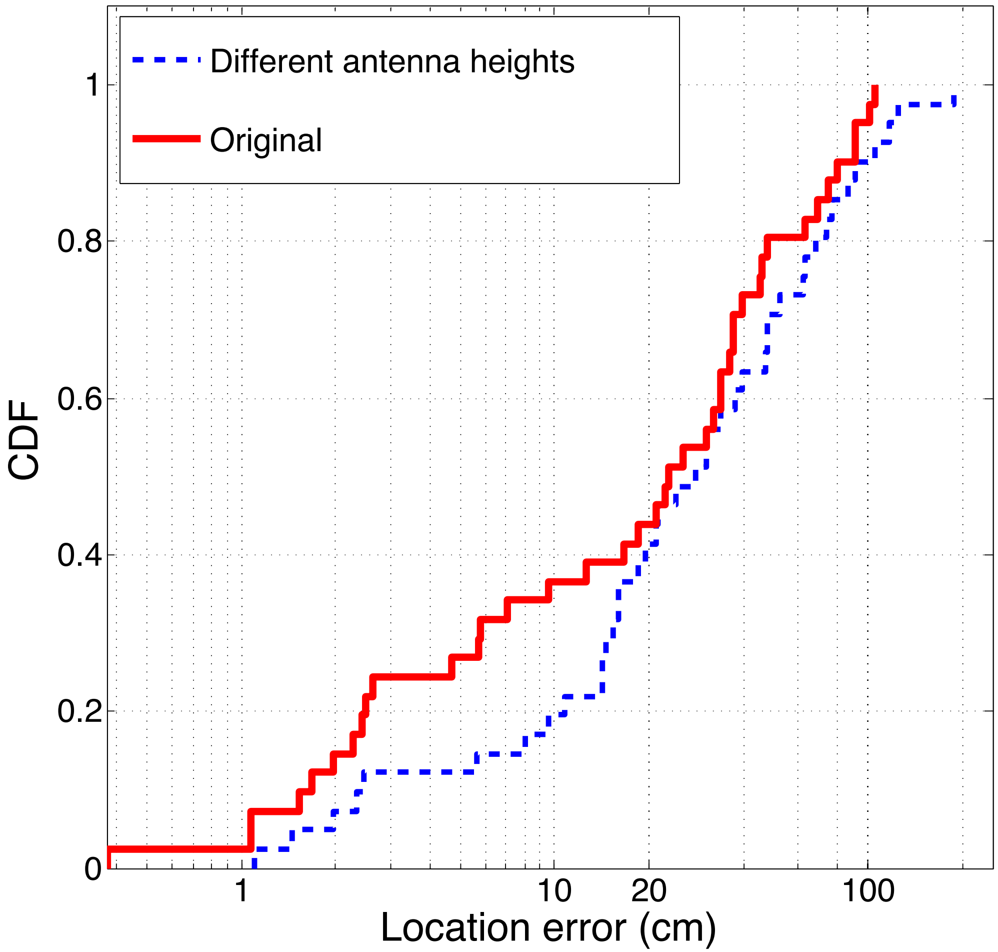


Evaluation

- Effect of number of APs on accuracy
- Multipath suppression improvement
- Effect of number of antennas on each AP
- **Effect of client-AP differences in height**

High accuracy despite AP-client height difference





Other characteristics of ArrayTrack

Small latency (1-3 packets needed)

Robust against low SNR

Robust against collision

Conclusions

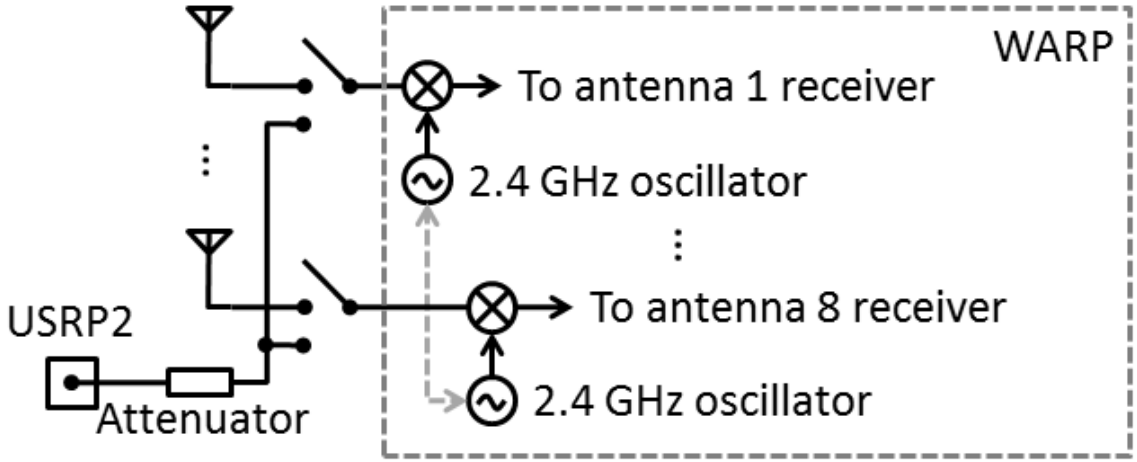
- **ArrayTrack:** a **robust, fast** and **responsive** localization system with a median accuracy level of **23 cm** (6 APs) and **one meter** (3 APs)
  - Novel multipath suppression and diversity synthesis algorithms
  - Uses only the WiFi infrastructure nearby
  - **Robust** against low SNR and packet collisions
  - **Fast** and **responsive:** requires only 1-3 packets

- Three dimensional tracking with two-dimensional array for future work

Thanks you!

Implementation challenges

- Wire connects WARPs to share the same sampling clock and RF oscillator
- USRP2 calibrates WARPs to remove WARP internal phase offsets
- Remove phase offsets due to hardware imperfections
  - Cables labeled with the same lengths are not exactly the same
  - SMA splitters are not fully balanced



AP-client antenna orientations

- Circularly-polarized antennas mitigate the performance drop