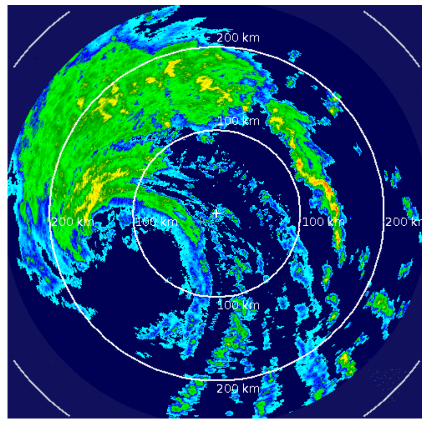
WiFi-based Indoor Localization

LOCALIZATION BASED ON FINGERPRINTING



RADAR:

An In-Building RF-based User Location and Tracking System

Main Goal

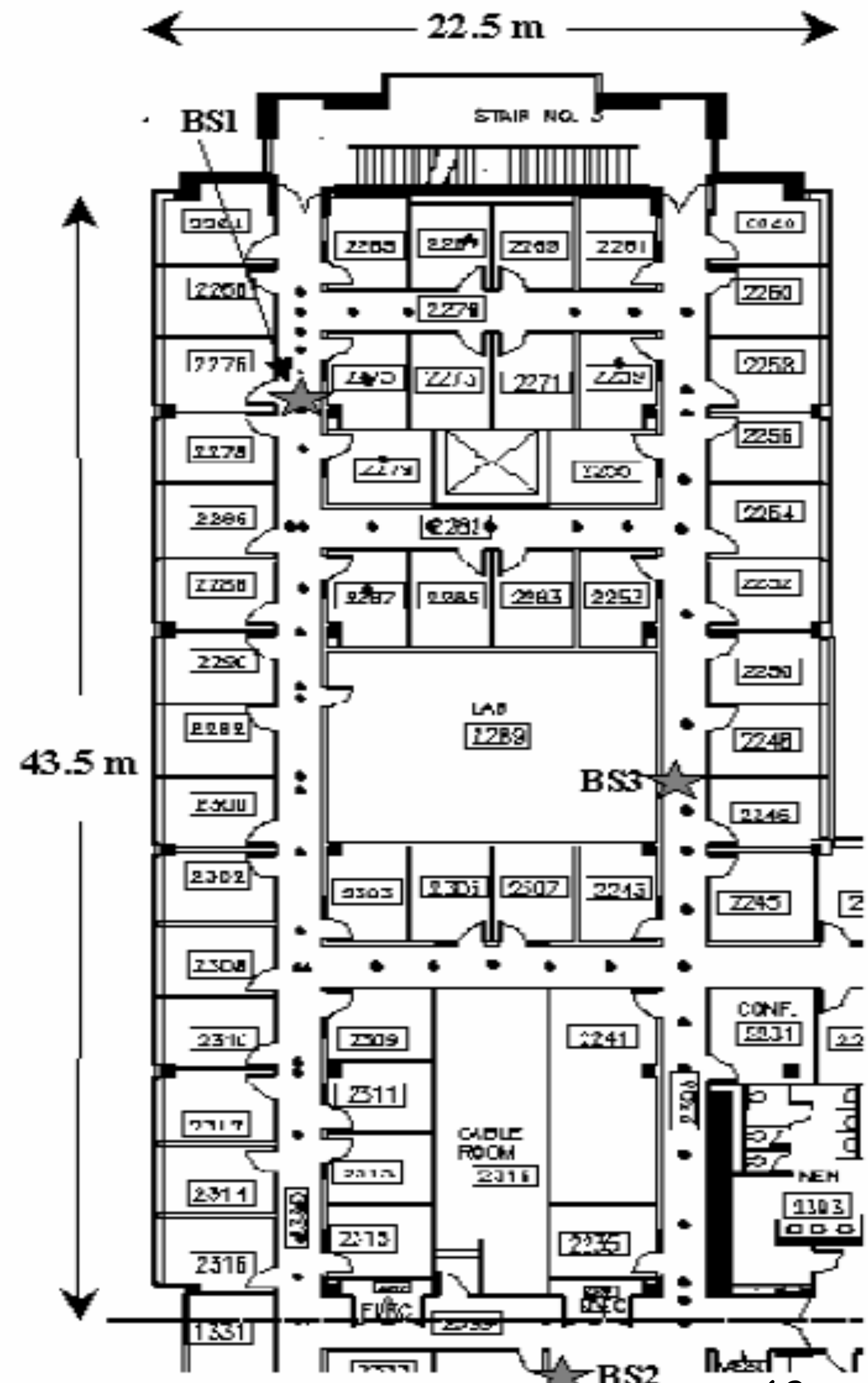
- Leverage the existing infrastructure of an indoor RF wireless LAN to build applications that take advantage of location information

Main Premise

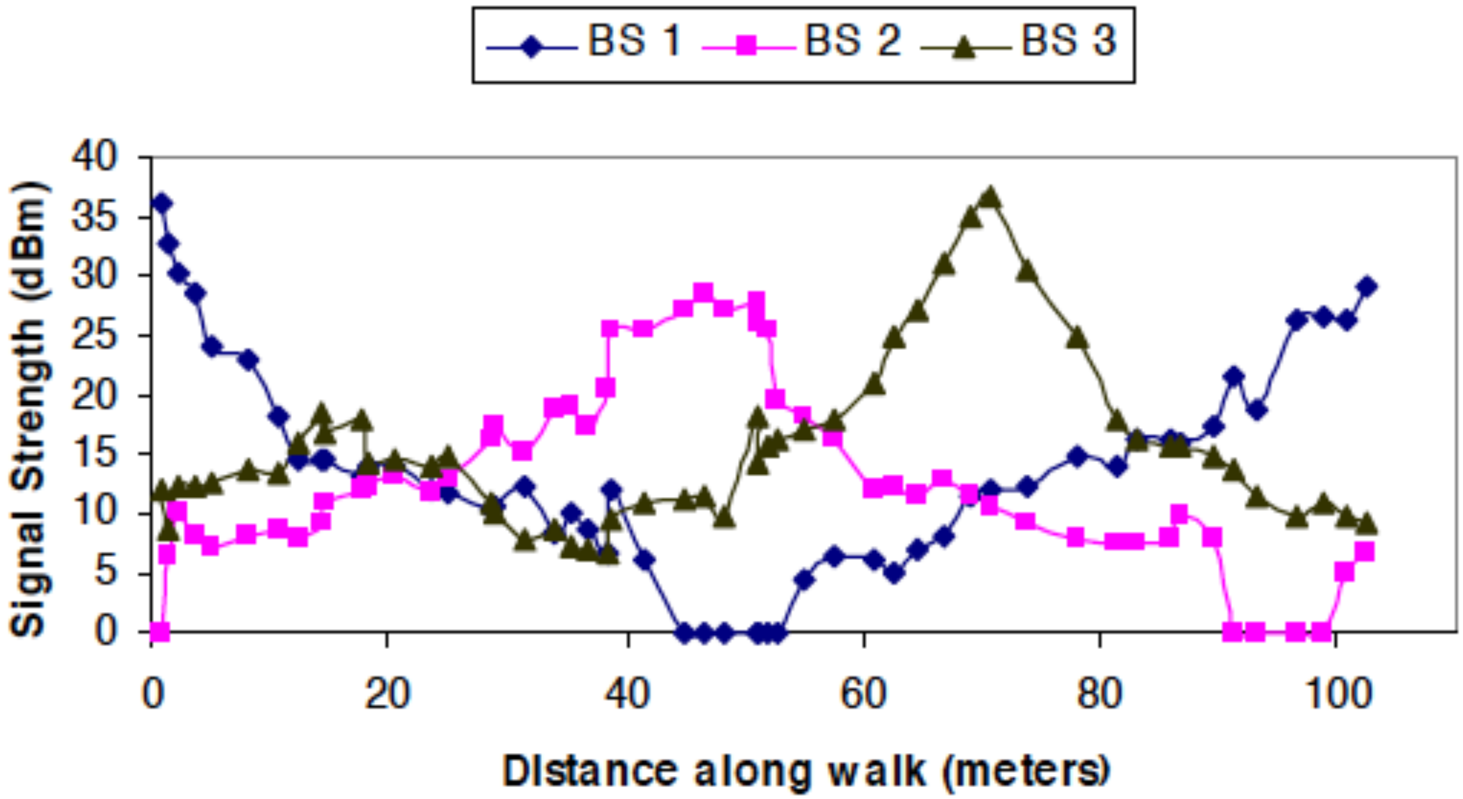
- There is a correlation between signal strength and location/distance

Experimental Testbed

- Black Dots = locations where signal strength info was collected
- Large Stars = Base Stations (BS)



How good an indicator of location is signal strength?



- User walks along the outer hallway of the floor in a counter-clockwise direction
- The walk begins and terminates close to BS1

Signal strength correlates well with distance

General Approach

- Key Idea: Map signal strengths to physical locations (Radio Fingerprinting)
- Inputs: Building geometry
- Training (Off-line) Phase: Construct a **Radio Map**
  - <location, Signal Strength (ss)> records in a database
- Operating Phase:
  - Extract SS from base station beacons
  - Transmit a location request to AP with SS as input
  - Find Radio Map entry that best matches the measured SS

Radio Map Construction (Off-Line)

Empirical Method

- Base Station emit beacons periodically: Measure SS based on beacons at various locations
- Record SS along with corresponding coordinates
  - User orientation needs to be included too
  - Tuples of the form $(x,y,z,d,s_1,\ldots,s_n)$
- Accurate but laborious

Mathematical Method

- Compute SS using a simple propagation model
  - Factor in path loss and wall attenuation
- More convenient but less accurate

Empirical Radio Map Construction

Measurement Based Map Construction

- Synchronize clocks on mobile host & base station
- Mobile hosts (it could have been the base station) broadcasts UDP packets
- Data are collected from 70 locations and 4 directions
- Each base station records SS at (t, x, y, d)
  - Time stamp (t)
  - Direction, d, user is facing (north, south, east, west)
  - User indicates location by clicking map on floor
- The data is combined in a common database where every entry is of the form (x,y,d,ss_i)
  - $i \in \{1,2,3\}$ corresponding to the three base stations

Operating Phase

- Input: The Radio Map and an observed signal strength (ss)
- Output: Location (x,y)
- Challenge: searching the radio map database for the best fit given a signal strength value

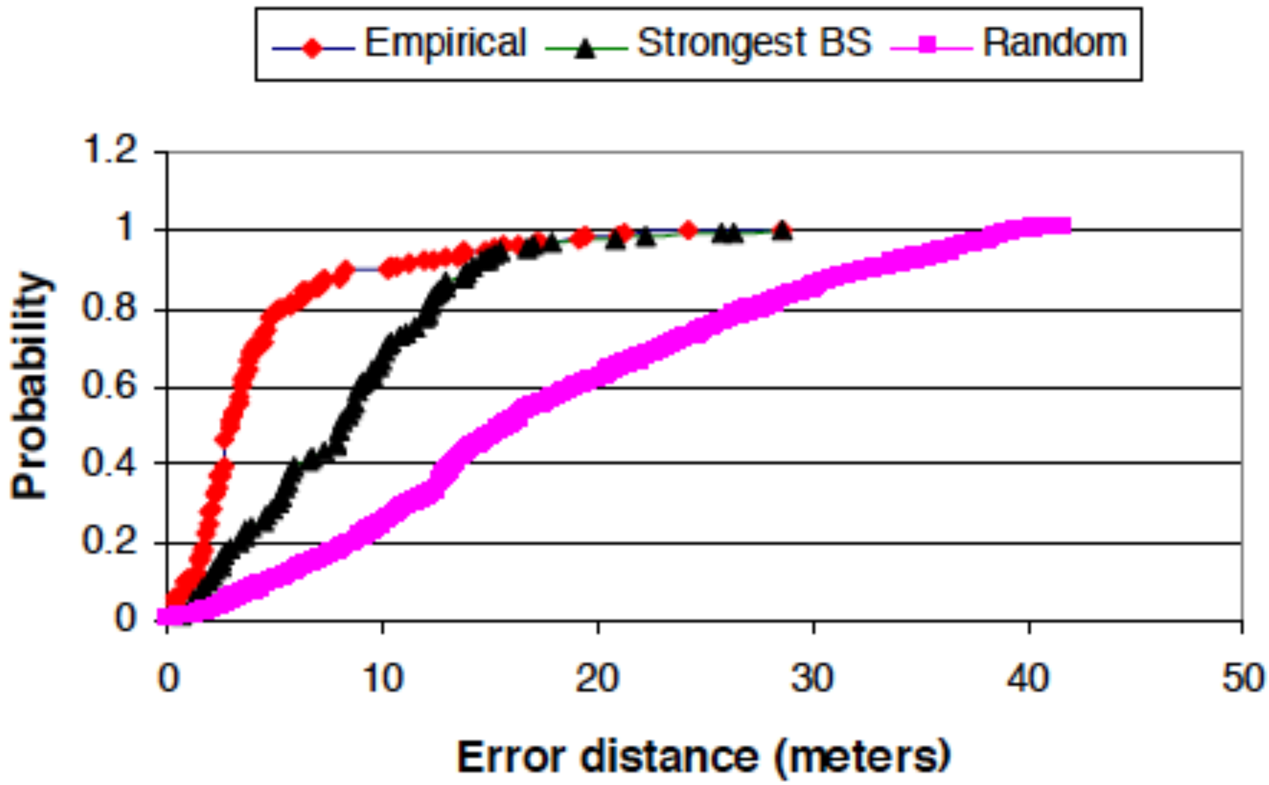
Mapping Signal Strength to Location

- Need a metric and a search methodology to compare multiple locations and pick the one that best matches the observed signal strength
- Approach: nearest neighbor(s) in signal space (NNSS)
  - Compute the distance (in signal space) between the observed set of SS measurements, (ss_1,ss_2,ss_3), and the SS, (ss'_1,ss'_2,ss'_3), at a fixed set of locations recorded in the radio map
  - Use the Euclidean distance measure $\mathrm{sqrt}((ss_1-ss'_1)^2+(ss_2-ss'_2)^2+(ss_3-ss'_3)^2)$
  - Search linearly the radio map database and return the (x,y,d) for which the Euclidian is minimized

Performance Evaluation

- Select at random one of the 70 locations in the radio map database
  - Remove it from the database
- Try to locate it using the rest of the entries in the database
- Compare with two simplistic schemes to quantify how worthwhile the increased sophistication of Radar is
  - Random Selection of a point in the radio map
  - Strongest Base Station Selection: same location as the base station with the strongest signal

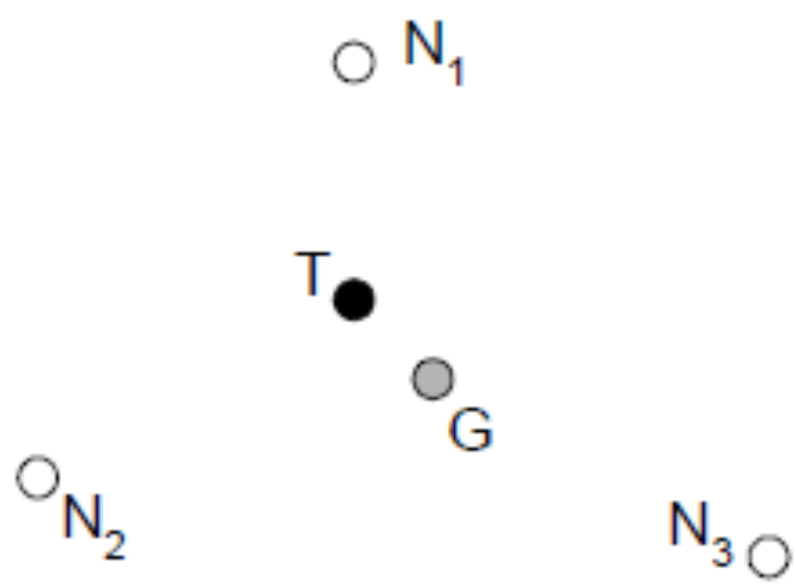
Location Estimate Error



Median error distance is 2.94 meters

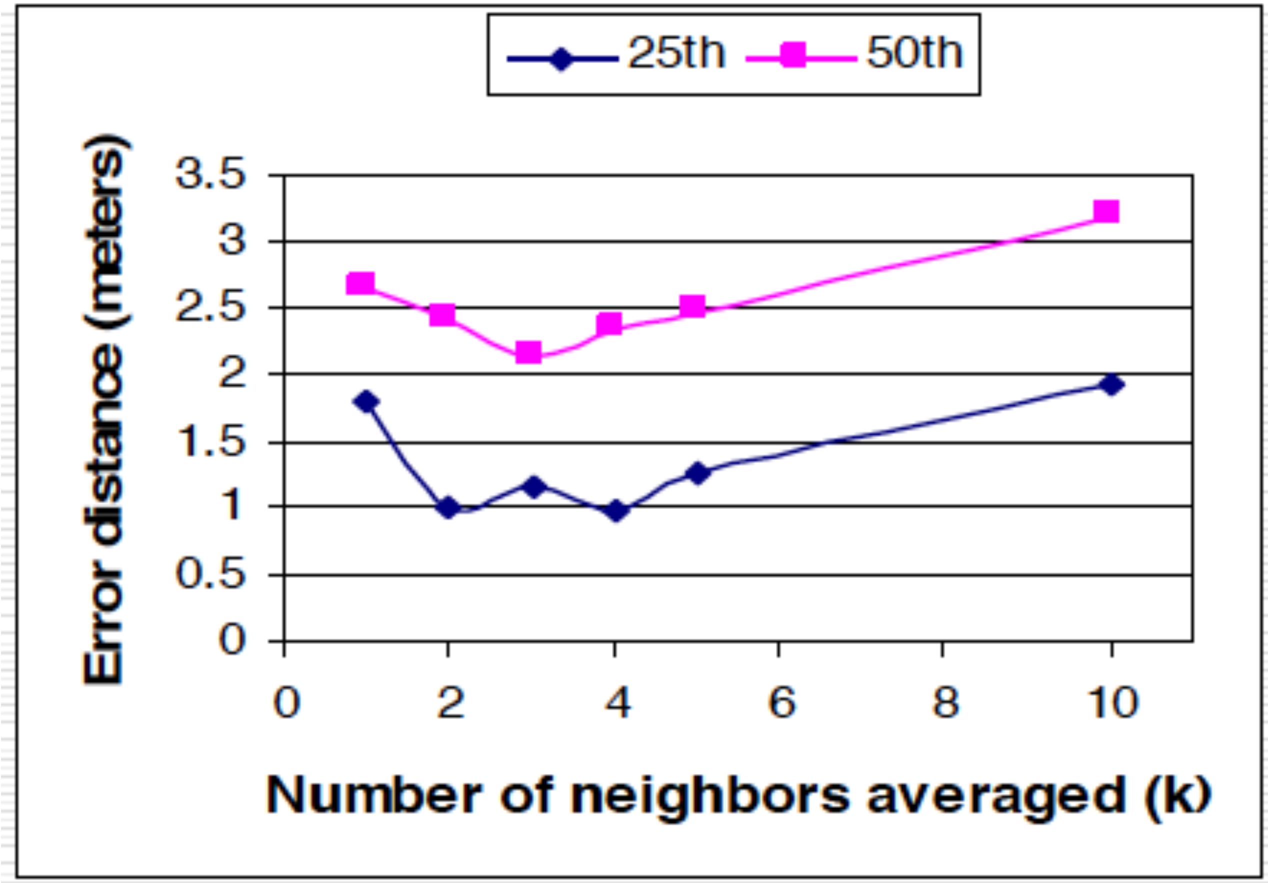
Multiple Nearest Neighbors

- Do not limit to just nearest data point (neighbor)
  - Average the coordinates of k nearest neighbors



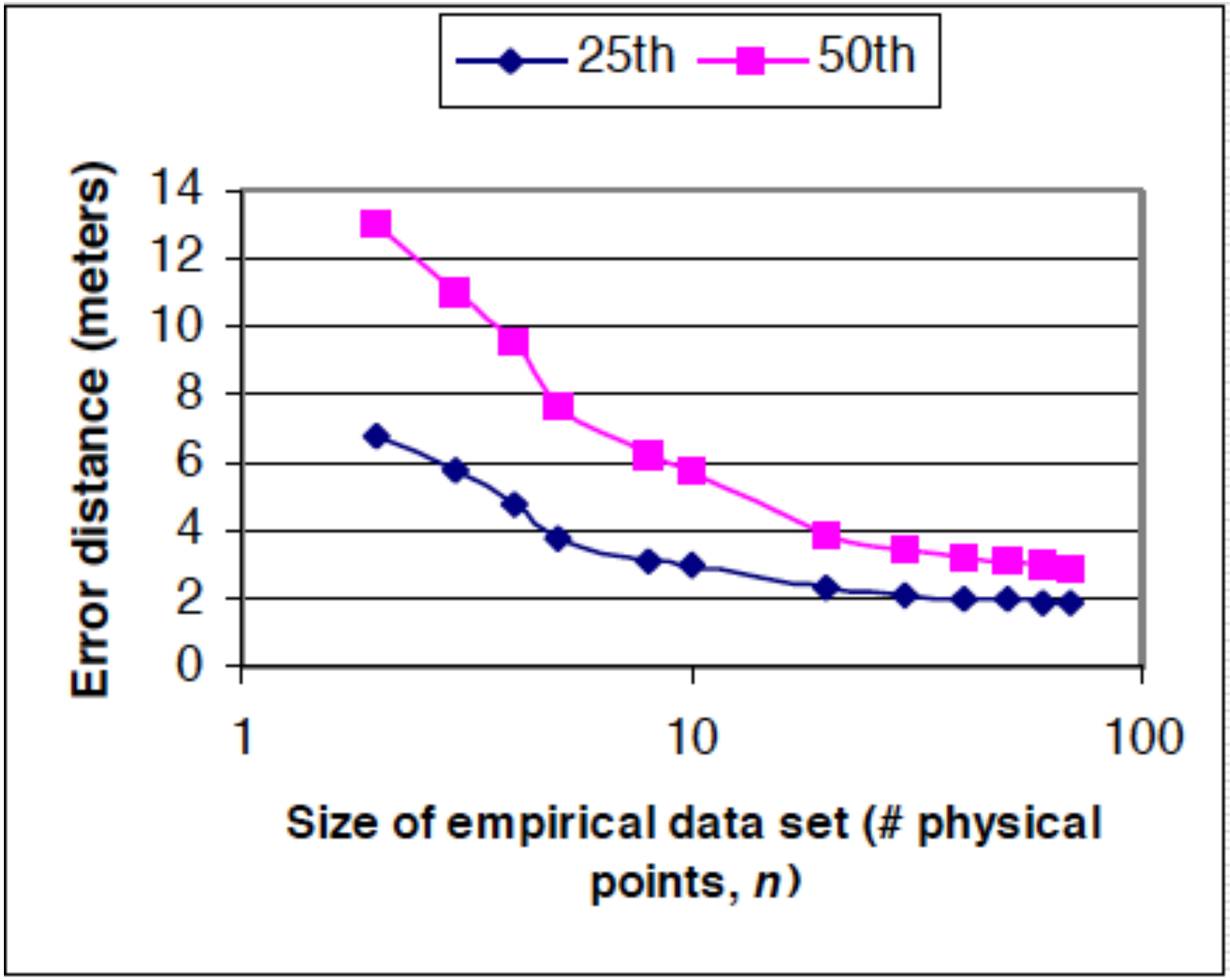
T: true location, G: guess

Performance with Averaging



Median error distance is 2.13 meters when averaging is done over 3 neighbors

How Extensive Does the Radio Map Have to Be?



Diminishing returns as the number of physical points mapped increases

Tracking a Mobile User

- Reduce the problem of tracking the mobile user to a sequence of location determination problems for a (nearly stationary) user
- 4 SS samples/second
- Use a sliding window of 10 samples to compute the mean signal strength on a continuous basis
- The median error distance observed was 3.5 meters, about 19% worse than that for a stationary user

Summary of the Empirical Method

- The empirical method is able to estimate user location with a high degree of accuracy
  - The median error distance is 2 to 3 meters, about the size of a typical office room
  - Much of the accuracy can be achieved with an empirical data set of about 40 physical points and about 3 real-time signal strength samples
- Long time to gather all the empirical data
- If BS moves, have to recollect all the data

LOCALIZATION BASED ON TIME OF FLIGHT (TOF)

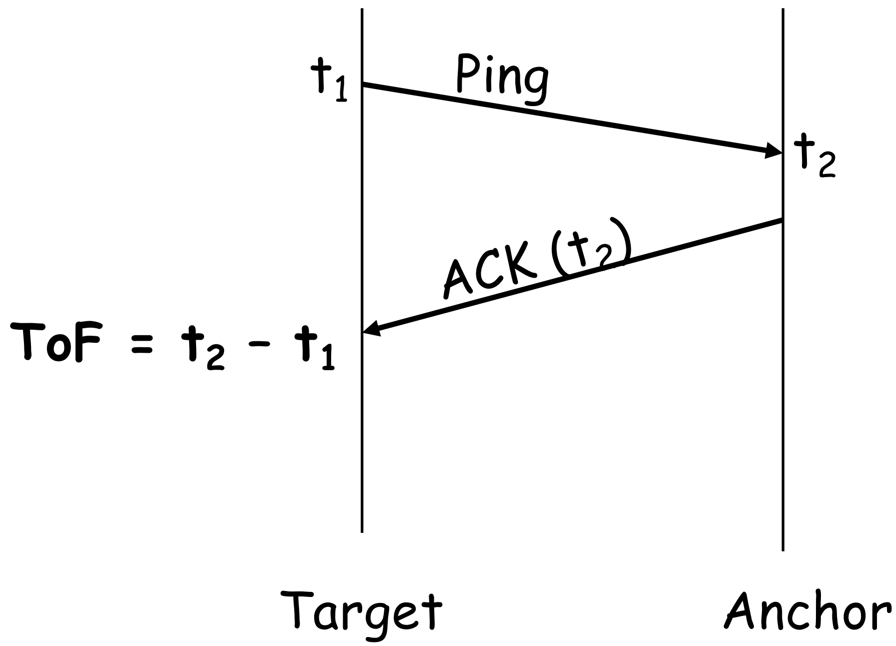
ToF-Based Localization

- The localization problem is reduced to a problem of computing the distance between the target a node and a set of anchor points whose coordinates are known

- Computing the distance between two devices
  - Equivalent to computing how long it takes for a wireless signals to travel the direct path between the devices – the Time of Flight (ToF)

Computing Time of Flight (ToF)

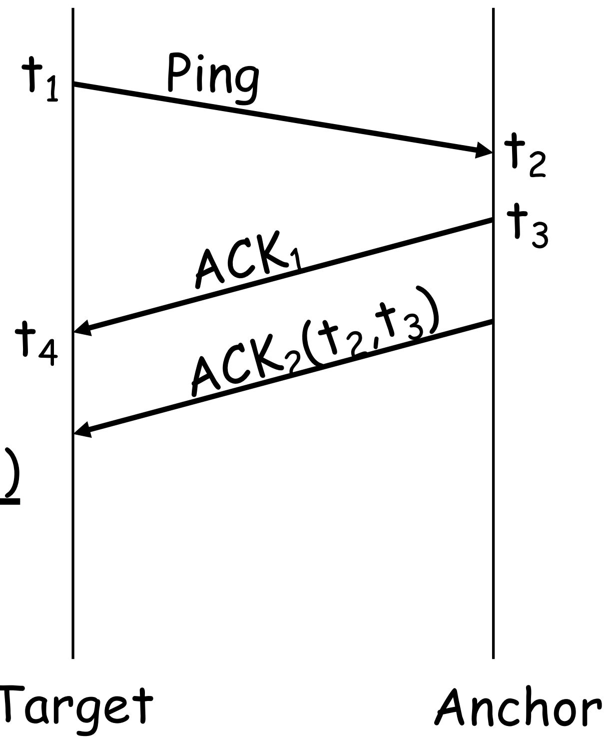
- Simplest approach



Any challenges ?

Computing Time of Flight (ToF)

- Two-way ranging (TWR)



$$ToF = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$$

Why is ACK_2 necessary?

WIFI FTM (IEEE 802.11AC)

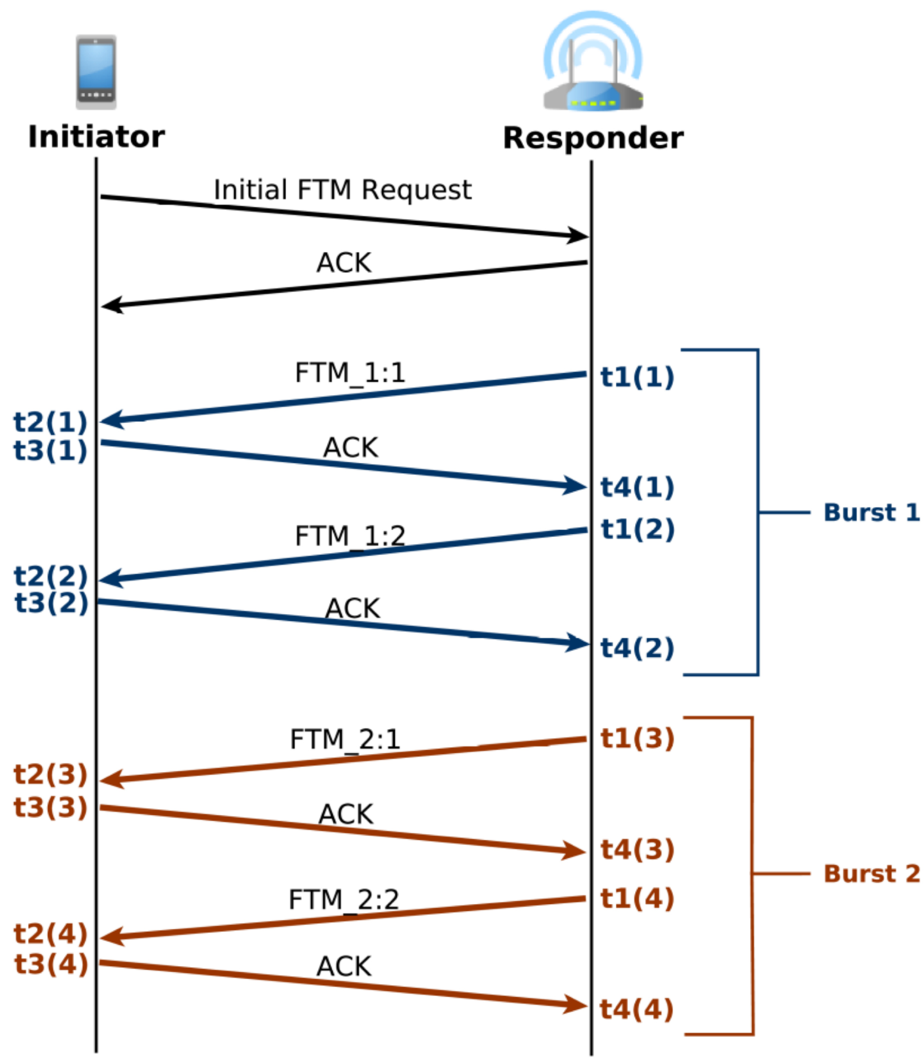
IEEE Fine Time Measurement

- Standardized as part of the IEEE 802.11-2016
  - Included as part of the 802.11mc amendment
- It enables a WiFi station to compute the distance to an access point in range without having to associate to the particular access point
  - It promises meter-level accuracy
- A standardized and native firmware implementation using clocks with picosecond resolution
- Supported by major WiFi manufacturers and it is adopted by the Android operating system
  - Google Pixel 2 and 3 phones, for example, are 802.11mc-compliant

IEEE Fine Time Measurement

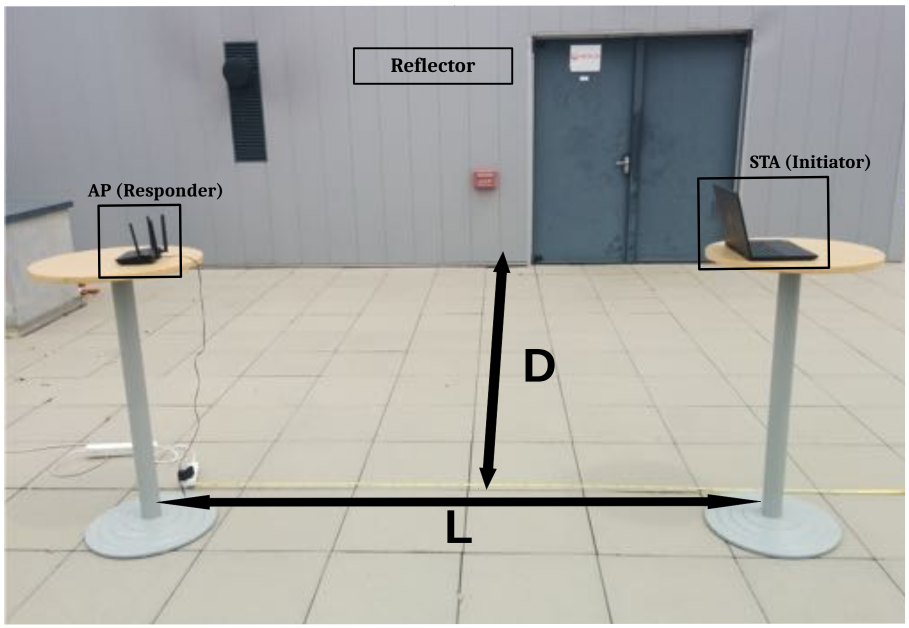
- The process starts with a WiFi station (called *initiator*) which scans for access points supporting FTM
- If an FTM-capable access point is detected, the initiator sends to the latter an FTM request frame
- Upon the reception that request, the access point can choose to ignore it, or to become a *responder*.
- The two stations start a series of (FTM, ACK) packet exchanges, called burst, allowing the initiator to estimate the round trip time (RTT) with the responder
- An FTM burst consists of the responder sending multiple FTM packets, which are all acknowledged by the initiator
  - Both stations capture the timestamps at which the burst packets are sent and received

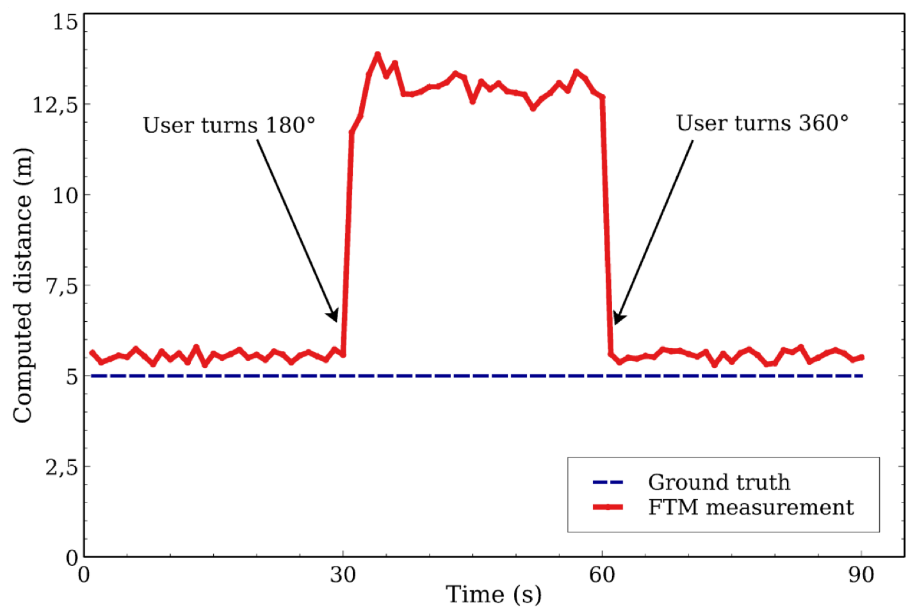
IEEE Fine Time Measurement



$$RTT = \frac{1}{N}\sum_{i=1}^{N}\left(t_4(i) - t_1(i)\right)$$

Does it work?


Reflector
AP (Responder)
STA (Initiator)
D
L


15
12,5
10
7,5
5
2,5
0
Computed distance (m)
0
30
60
90
Time (s)
User turns 180°
User turns 360°
Ground truth
FTM measurement

What happened?