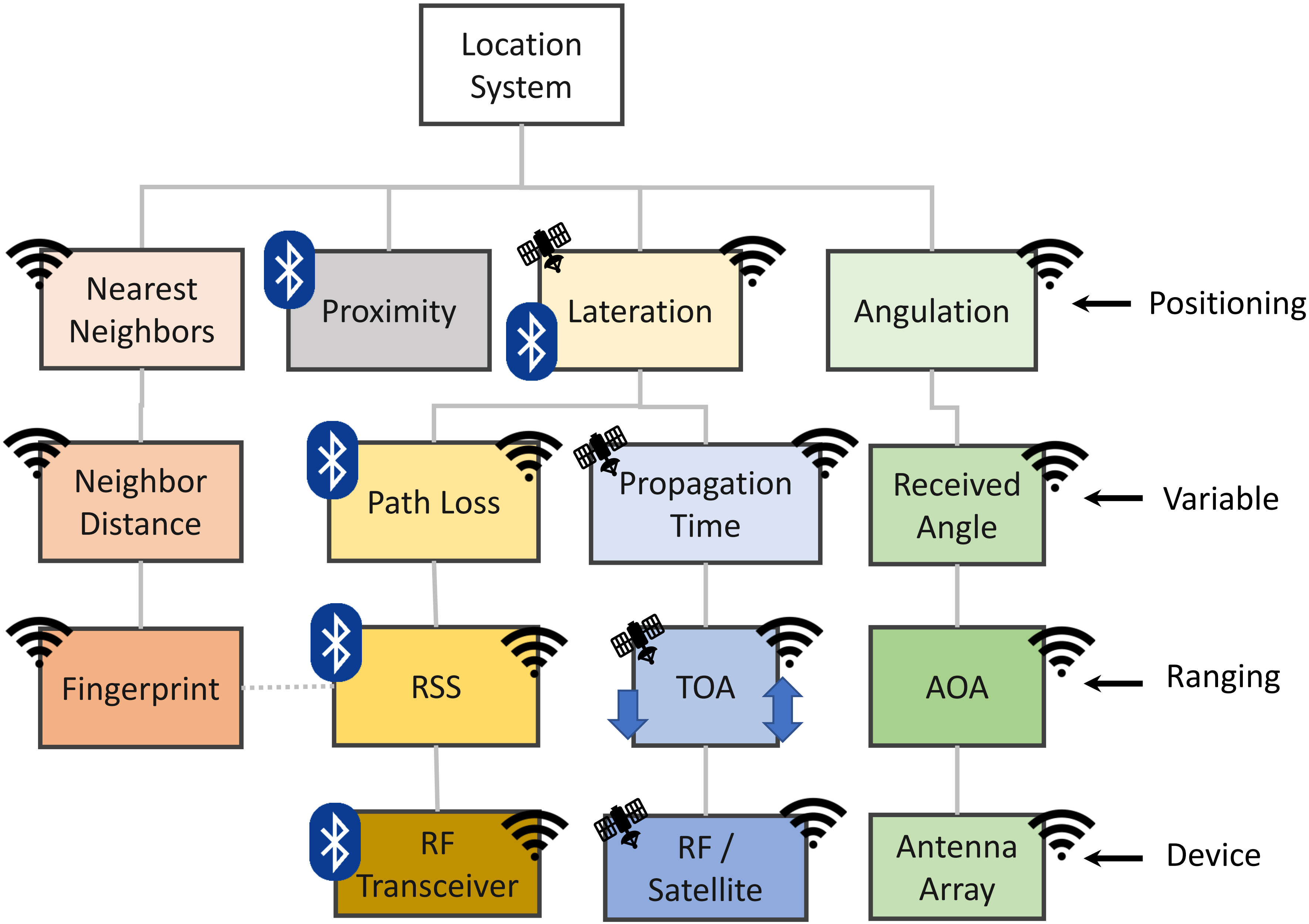
Mobile Indoor Positioning

CSCI3310

Mobile Computing & Application Development

Outline

- Positioning from Global to Indoor
- Beacon-based Positioning Techniques
  - Proximity
  - Received Signal Strength
  - Fingerprint
  - Time/Angle of Arrival
- BLE vs WiFi Positioning

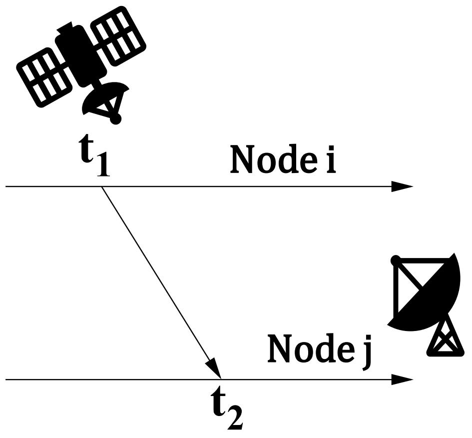

Location System
Nearest Neighbors
Proximity
Lateration
Angulation
Positioning
Neighbor Distance
Path Loss
Propagation Time
Received Angle
Variable
Fingerprint
RSS
TOA
AOA
Ranging
RF Transceiver
RF / Satellite
Antenna Array
Device

Time of Arrival Positioning

Time of Arrival (ToA, time of flight)

distance between sender and receiver of a signal can be determined using the measured signal propagation time and known signal velocity

- One-way ToA
  - one-way propagation of signal $$dist_{ij} = (t_2 - t_1) * v$$
  - requires highly accurate synchronization of sender and receiver clocks



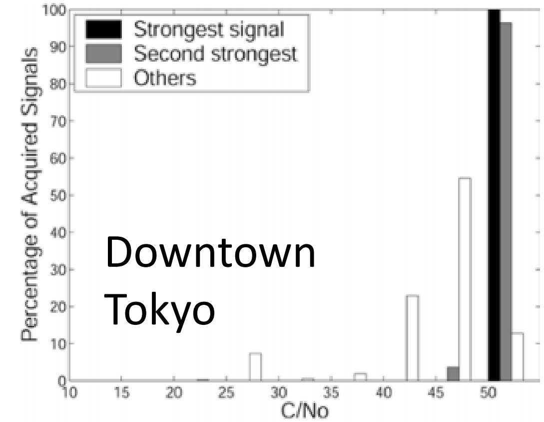
GPS indoor?

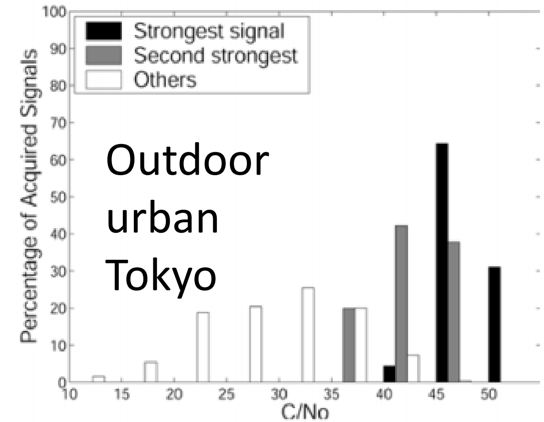
Various problems happened when GPS algorithm is being put into indoor usage

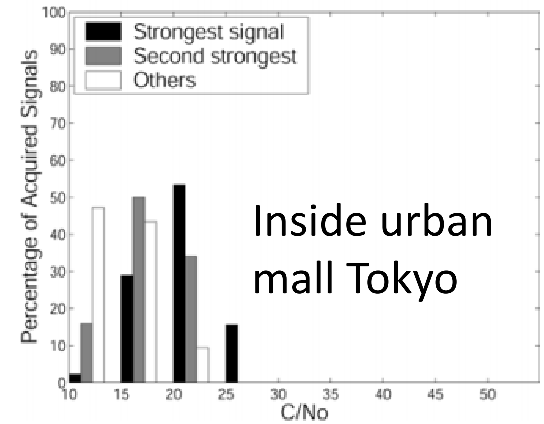
Signal attenuation :

- Level of C/N_0 – **signal** power divided by **noise** spectral density (SNR) denoting a measure of sensitivity of a system

- Chart on right indicated that urban & indoor environment poses severe challenge to GPS signal acquisition







From Outdoor to Indoor Positioning

- GPS provides positioning information to mobile devices in an outdoor environment, but difficult to be useful in indoor environment

- Indoor positioning system are being implemented to provide more user experiences in indoor situation such as shopping mall, museum etc.

- No silver-bullet technology exists for indoor positioning so far

Local Positioning System

- a navigation system that provides location information anywhere within the coverage of the network
- require an **unobstructed line of sight** to **three or more signaling beacons** of which the exact position locally is known

Local Positioning - Beacons

- Beacons include **cellular** base stations (Cell-ID), **Wi-Fi** Access Points (AP), and **radio broadcast** transmitters
- useful in very poor signal conditions, e.g., in city, these signals may suffer multipath propagation
- Basic concept : **calculate the position** like that of GPS, with satellites now replaced **with beacons**
- The accuracy of network-based techniques varies, with cell identification as the least accurate and triangulation as moderately accurate

Bluetooth BLE

- **One-way** advertisements of small packets of data which are:
  - **broadcast** at regular intervals through radio waves
  - Pick up by BLE enabled devices nearby, triggering for corresponding events

Bluetooth BLE

- Apple standardized BLE packet into 3 components
  - Universally Unique Identifier
  - Major value
  - Minor value

proximityUUID	major (optional)	minor (optional)
a unique UUID to distinguish your beacons from other beacons	used to specify a particular beacon within a group	used to identify specific beacons
Same UUID for a company's beacons (i.e. 064cc638-2629-5f5e-a6b0-b66af78d7b5f)	Arbitrary numeric value: Stores in New York = 1 Stores in San Francisco = 2	Arbitrary numeric value: Storefront = 5 Shoes section = 6 Cashier = 7

Beacon based Positioning

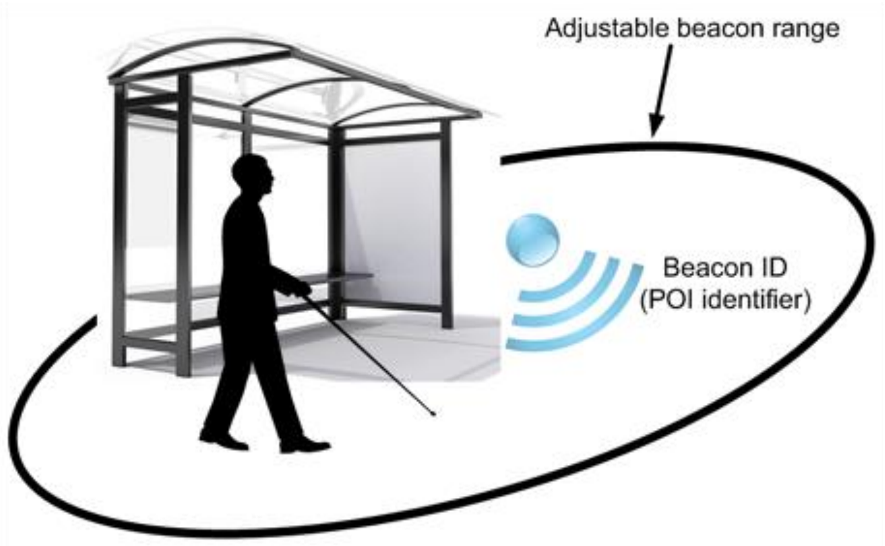
- Can be broadly classified as:

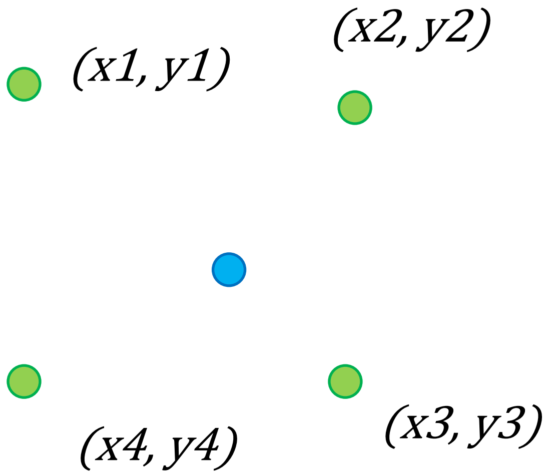
1. Range-free Localization
    - **Proximity,** based on surrounding beacons' locations

2. Range-based Localization
    - **Lateration**, measure distances from reference nodes
    - **Angulation**, rely on angles to reference nodes
    - **Fingerprint**, match received signal pattern

Range-free Proximity

- Used in localization of beacons
- **No (reliable) ranging information** of individual beacon
- Locations of surrounding beacons are obtained through some broadcasts

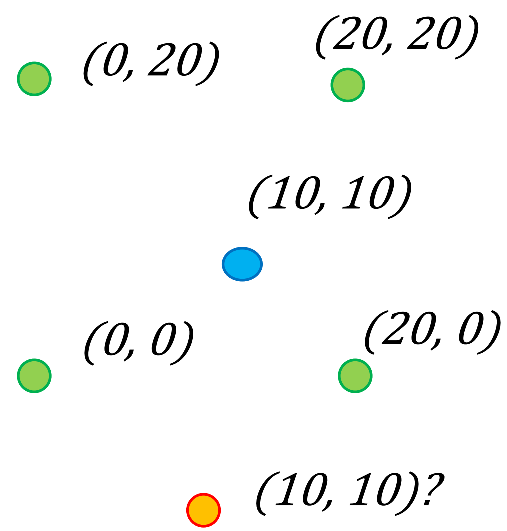




Centroid Algorithm (Proximity)

- all possible reference node's locations are being broadcasted
- Target node use these information to **compute its own location estimate**

$$(x_{target}, y_{target}) = \left(\frac{1}{N}\sum_{i=1}^{N} x_i, \frac{1}{N}\sum_{i=1}^{N} y_i \right)$$



(x, y) *coordinates of Beacons*

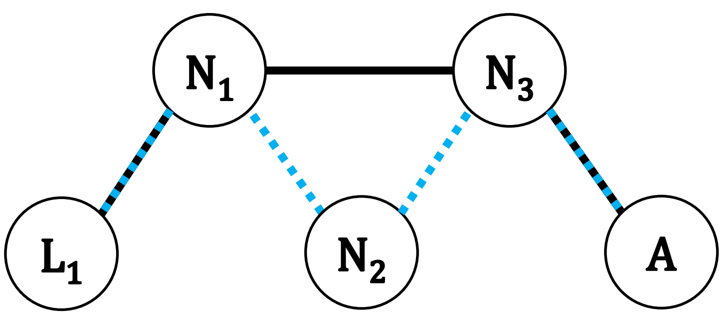
N: *total number of reference nodes that target node can detect*

- Problem : Not accurate enough when target node near edge of network

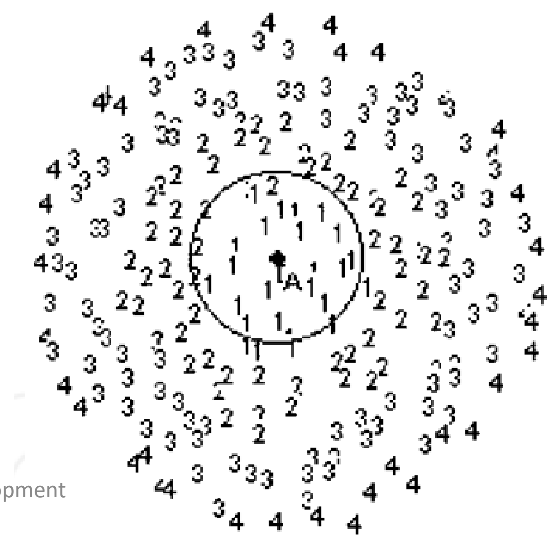
DV-hop Algorithm (Proximity)

To avoid centroid algorithm's boundary problem, **distance measure** can be taken into account

1. All Beacon nodes broadcast node information, all surrounding nodes receive first-hand can store these **distance vectors**
2. First-hand nodes diffuse vector outward with **hop count** increased
3. If node receive vector with higher hop-count as compared to previous hop value, no action taken



The hop count from $\mathbf{L_1}$ to **A** is **3** instead of 4



DV-hop Algorithm (Proximity)

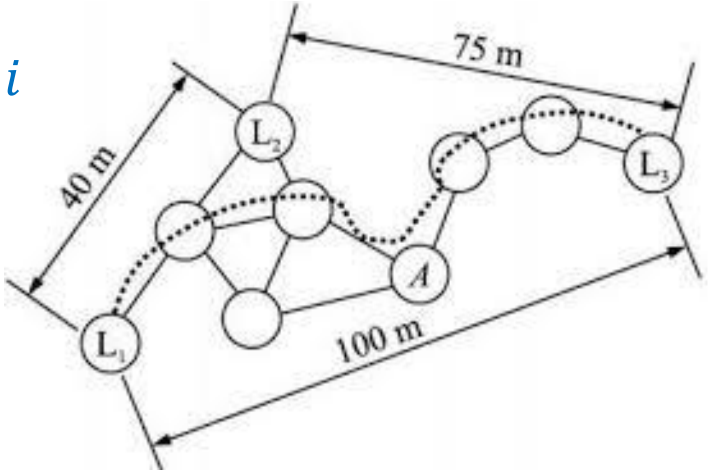
- All beacons have a distance vector of all other beacons
- Find the average distance between hops using

$$HopSize_i = \left(\frac{\sum \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum h_j} \right)$$

$HopSize_i$: average single hop distance for node i

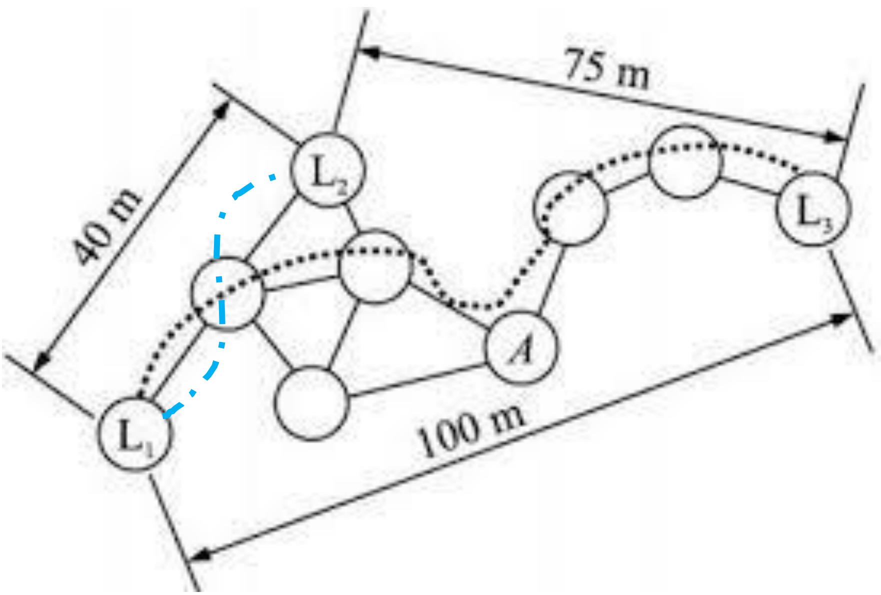
(x_j, y_j) : location of all other beacons

h_j hop-count distance from j to i



DV-hop Example

- $\mathbf{L_1}$'s **average hop length** $= \frac{\mathbf{100+40}}{\mathbf{6+2}} = 17.5$,
- **Distance between** A and $\mathrm{L_1} = 17.5 \times \mathbf{3} = 52.5$
- Similar calculation applies to $\mathbf{L_2}$ and $\mathbf{L_3}$, then
- $\mathbf{A}$'s position can be computed through **trilateration**



Getting Range from Beacon Signal

Range in **distance/angle** can be obtained in several means:

- Received Signal Strength Attenuation (RSS)
- "Fingerprint"
- Angle of Arrival (AoA)
- Time of Arrival (ToA)

- Possible choices of signal:
  - **Wi-Fi** was being investigated due to its widespread implementation
  - **Bluetooth Low Energy (BLE)** also provide ranging info

Received Signal Strength

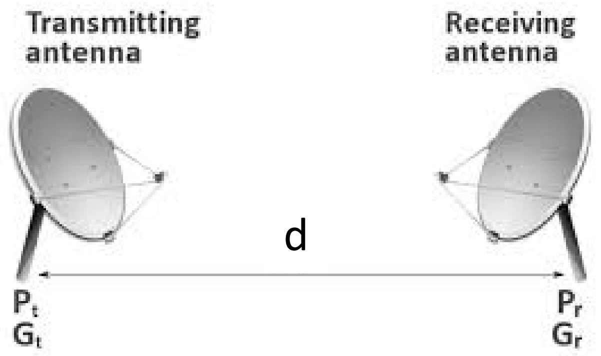
Received Signal Strength (RSS)

In free space, RSS degrades with square of distance

- expressed by [Friis transmission equation]

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi)^2 d^2}$$

where P are power at transmitter/receiver, λ is the wavelength, D are antenna gains, d is distance



- Strength of received signal in a Beacon (RSS) have the relationship

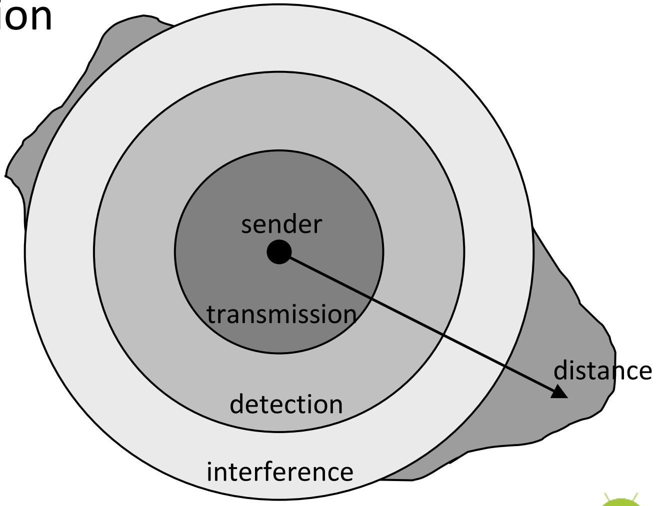
$$P_r \propto \frac{1}{d^2}$$

- P_r: received power at a distance d from transmitter

Received Signal Strength Indicator

Received Signal Strength (RSS)

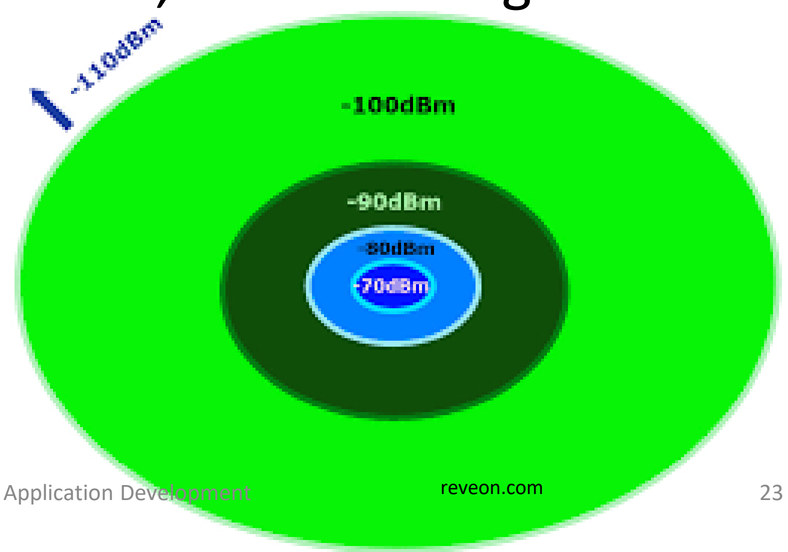
- signal decays with distance
- many devices measure signal strength with received signal strength indicator (RSSI)
- **Implemented in most wireless** communication standards (IEEE802.11, 802.15.4)
  - vendor-specific interpretation and representation
  - typical RSSI values are in range of 0..RSSI_Max
  - common values for RSSI_Max: 100, 128, 255



Received Signal Power

- RSSI represents condition of received power level
- Since RSSI varies greatly between chipset manufacturers, microcontroller will convert it into digital value (in ***dBm***) for further processing
- A more standardized, absolute measure of signal strength: received signal power, which is measured in decibels, or dBm on a logarithmic scale.

RSSI	Signal Strength
> -70 dBm	Excellent
-70 dBm to -85 dBm	Good
-86 dBm to -100 dBm	Fair
< -100 dBm	Poor
-110 dBm	No signal



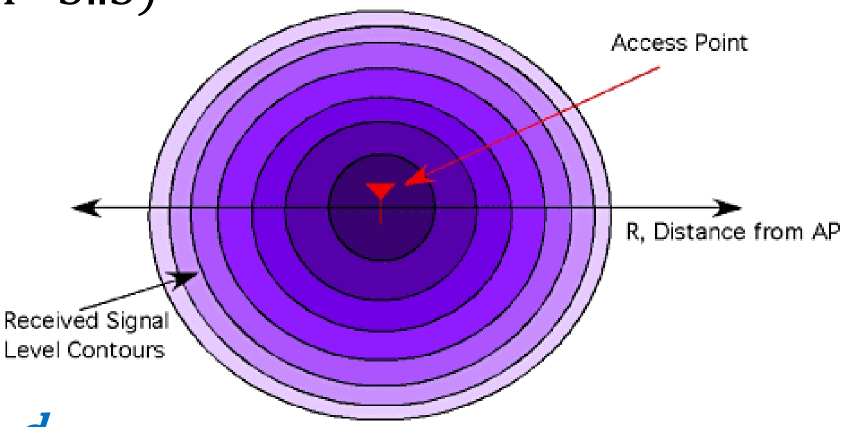
Signal Strength Ranging

Positioning with Received Signal Strength (RSS)

- In practice, the actual attenuation depends on multipath propagation effects, reflections, noise, etc.
  - realistic models replace d^2 with d^n (n=3..5)
- Thus, the path loss can be differed,

$$P_r \propto \frac{1}{d^2}$$

$$P_r = \frac{P_{(d_0)}}{(d/d_0)^n} \qquad (1)$$



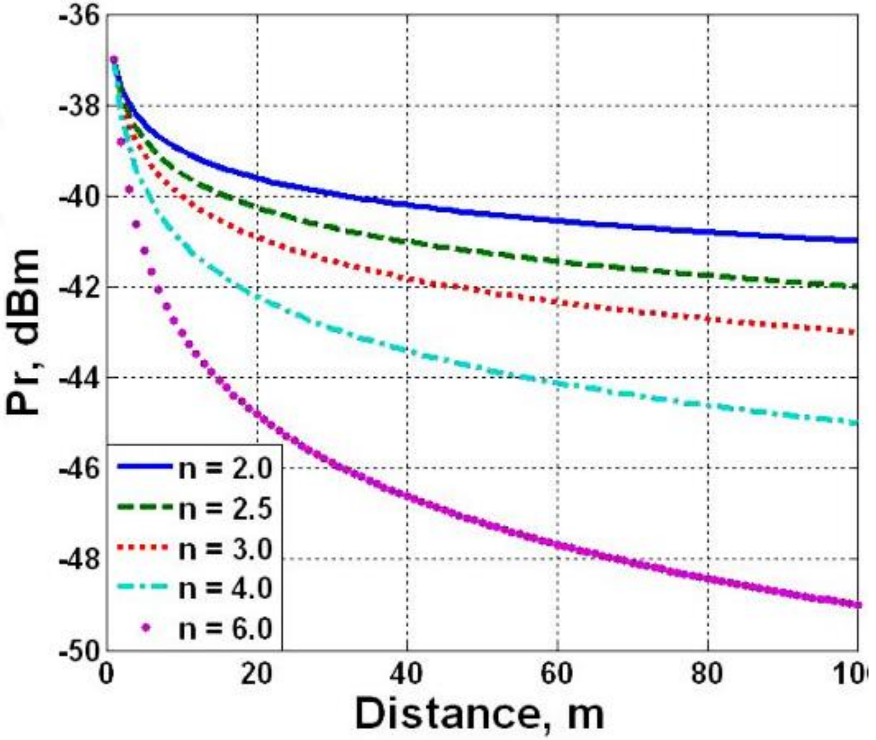
where $P_{(d_0)}$ is received power measured at distance d_0

d_0: fixed constant for 1 meter

n: path loss exponent for environmental /device characterization

Path Loss Model (RSS)

- Radio signal propagation model to model nature of **signal attenuation** over space
- Convert **RSS value to distance value**
- **Non-linear Path Loss** becomes more serious as size of indoor area is small
- Resultant location error in indoor becomes obvious



iBeacon (iOS)

Ranging : the relative **distance to a beacon**

- depends on detecting the **strength of Bluetooth low-energy radio signals,**
- Return an array of all iBeacons found along with their properties (UUID, etc.)
- Accuracy is lessened by walls, doors, and other physical objects
- Works only in the foreground

Beacon (Android)

- iBeacon capability is also available on Android, though not official
- http://altbeacon.org/

Tools

- AltBeacon Locate Android Utility for detecting AltBeacons
- QuickBeacon Android Utility for transmitting as an AltBeacon
- Beacon Simulator Android Utility for transmitting as an AltBeacon or other beacon formats, with management of different configurations

Code

- Android Beacon Library Android Library for detecting AltBeacon Transmissions
- Linux AltBeacon Reference Implementation Example code using the BlueZ Bluetooth protocol stack

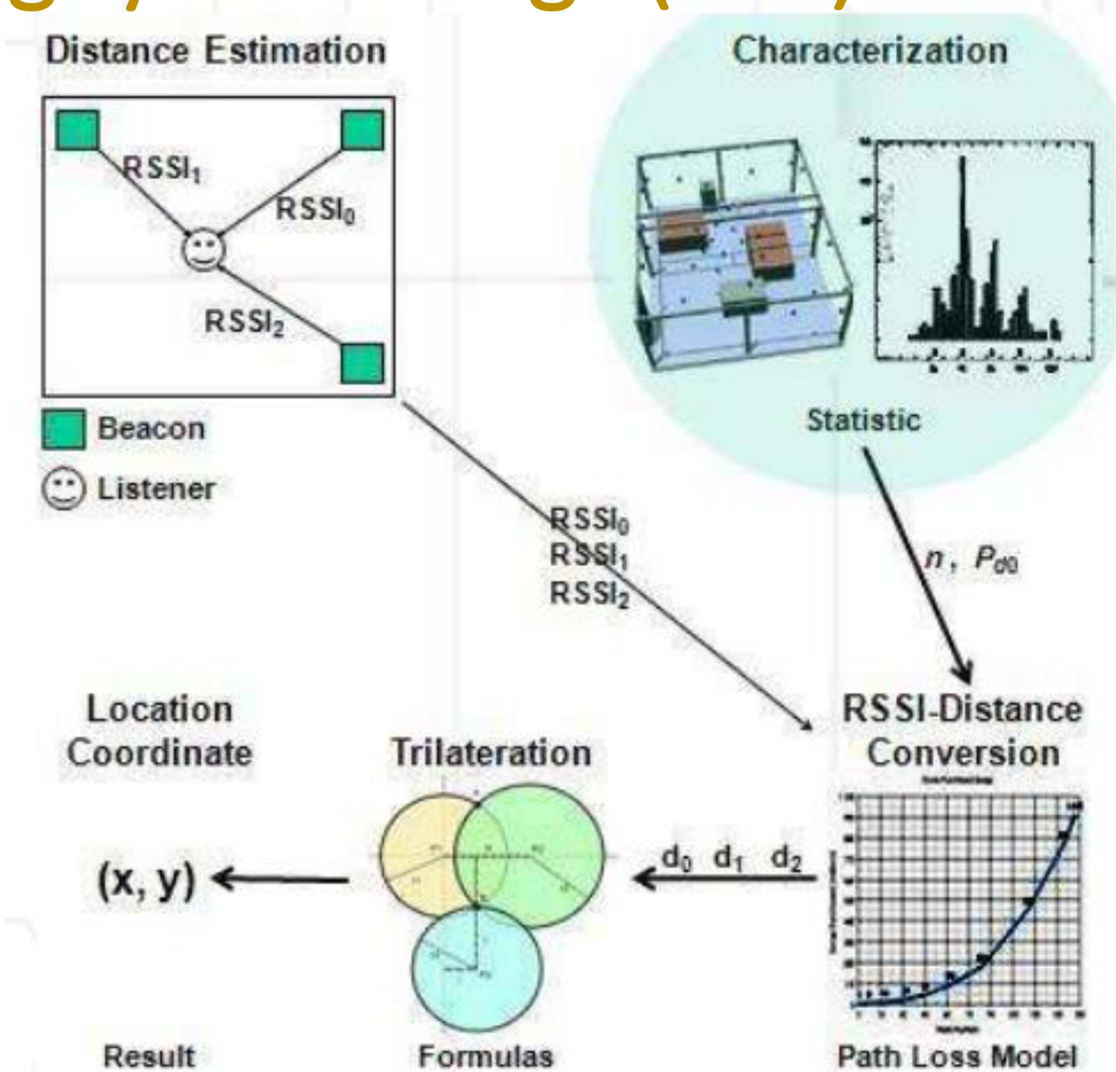
Location Tracking System Design (RSSI)

1. Collect **RSSI**

2. Calibrate **environmental characterization** to find parameters for that area;

3. Recover distance values from **path loss model** with **RSSI** values from reference nodes and **environmental parameters**;

4. Apply **Trilaterion**



RSSI Measurement

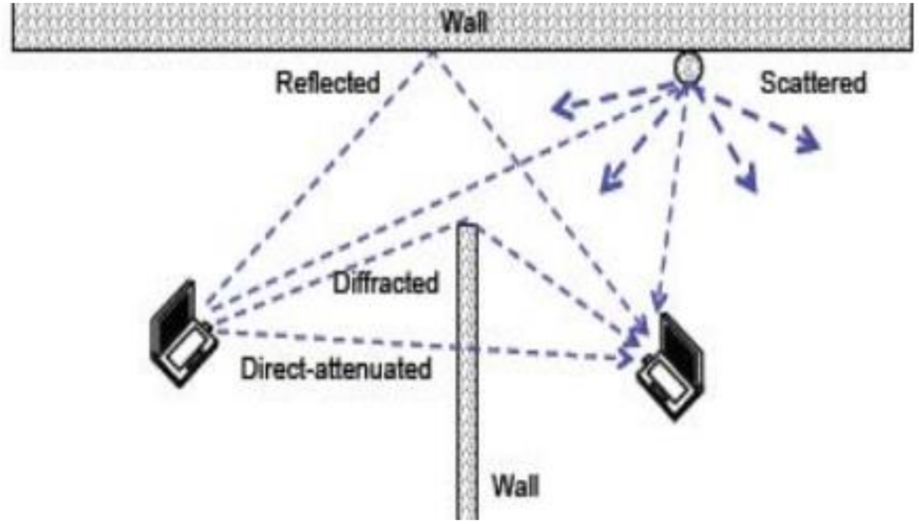
- RSSI value collected from Beacon nodes
- Not exactly received power at RF pins of receiver
- Converted to power value in ***dBm*** by

$$P_i = (RSSI_i + RSSI_{offset})$$

- $RSSI_{offset}$ found empirically from front end gain, approx. -45 dBm
- Make sure actual received power has range from -100 to 0 dBm , with 0 dBm indicates maximum received power

Indoor Localization Issues

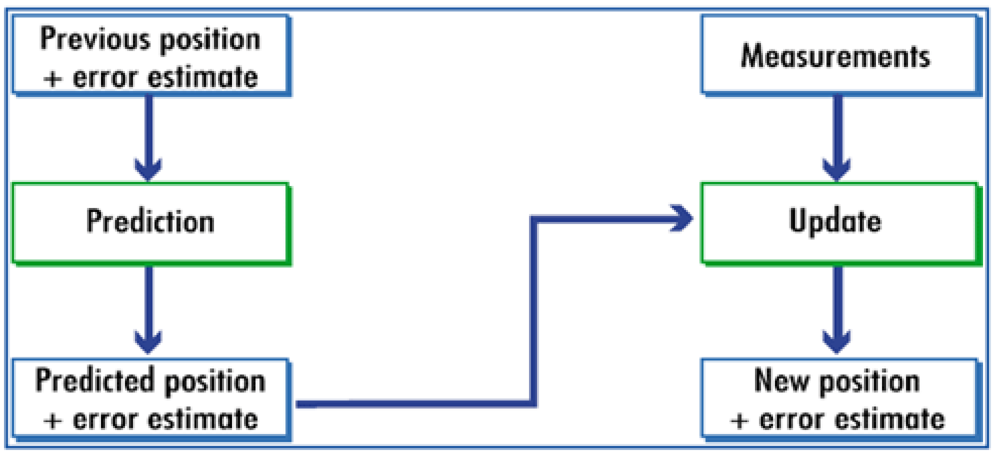
- Signal strength is nonlinear due to multi-path fading and indoor shadowing
- Multi-path fading: scenes in which no line of sight between transmitter and receiver, and many buildings and other objects attenuate, reflect, refract and diffract the signal

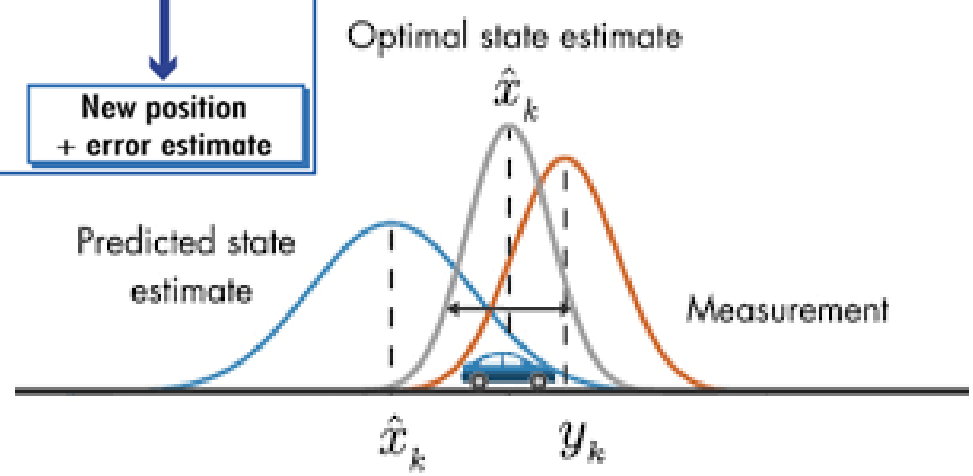


- Become more serious as the indoor area smaller

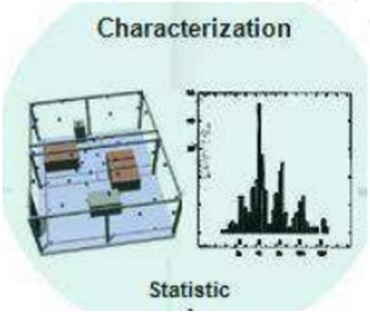
RSSI Signal Improvement

- **Kalman filter** can be used to improve signal value by optimizing RSSI <u>estimate through raw RSSI measurement and prediction</u>



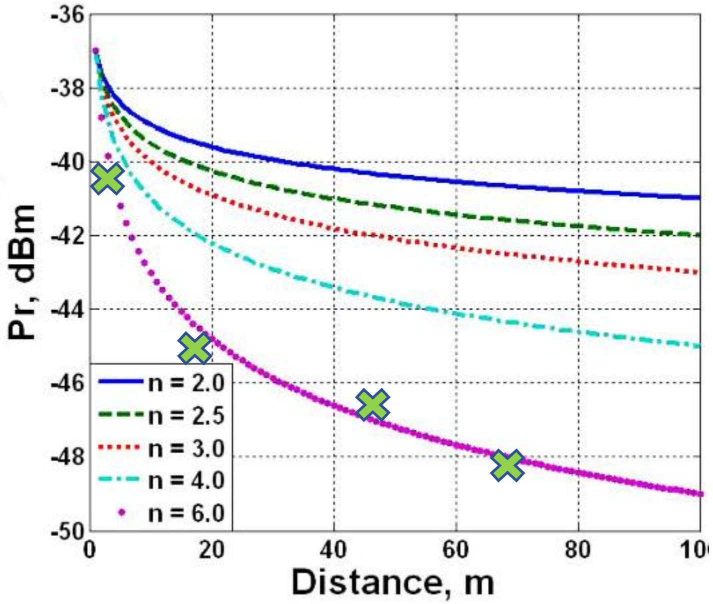


Environmental Characterization



1. Measure received power $P_{r(d_0)}$ at distance d_0 (1 meter) to transmitter
2. Measured received power P_r by moving receiver to other locations and
3. Estimate path loss exponent n by curve fitting

$$P_r = \frac{P_{(d_0)}}{(d/d_0)^n} \quad (1)$$

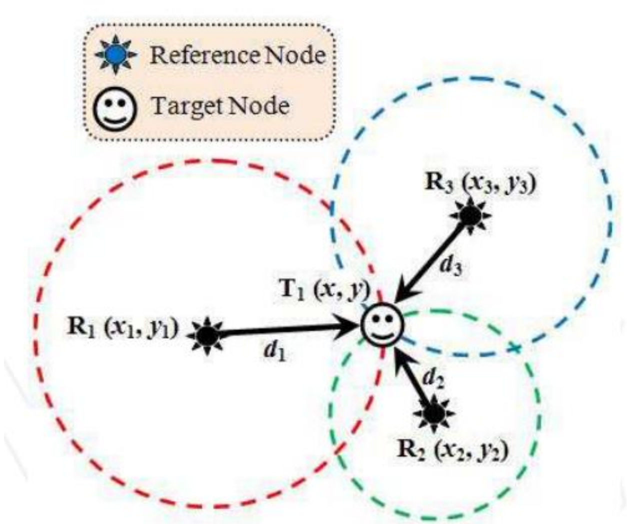


RSSI-Distance Conversion

- Log-distance path loss model will return the distance value

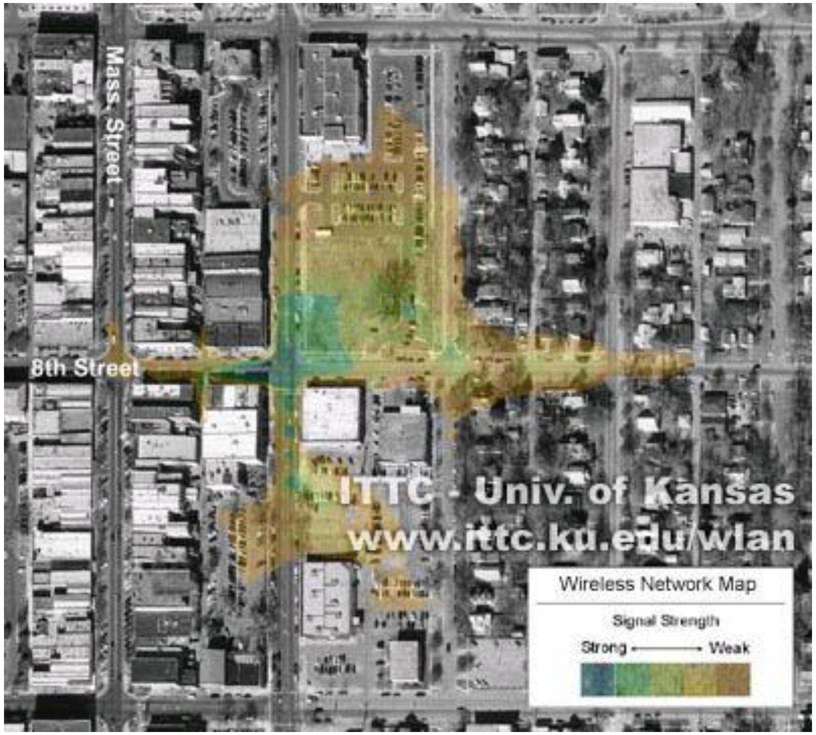
$$d = d_0 \exp\left(\frac{P_{r(d0)} - P_{r(d)}}{10n}\right)$$

- Final location can be computed through trilateration or multi-lateration



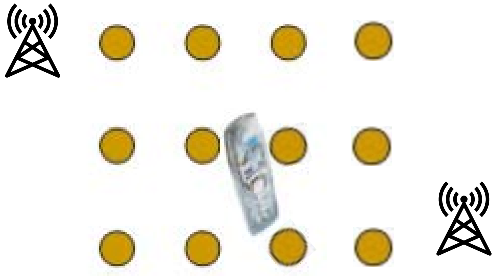
Wi-Fi Positioning Systems

- Wi-Fi chips in devices detect the range via **RSSI, AOA** or **TOA**
- Client devices can detect APs in two ways
  - Passively listening on 802.11 channels for beacon frames
  - Initiate scan by sending requests which AP reply
- Wi-Fi APs broadcast signals up to 100m



Fingerprint Positioning

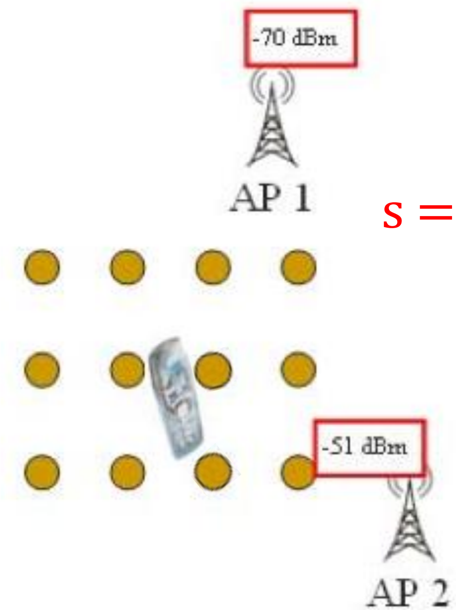
- RSS Fingerprint positioning takes advantages of two properties observed by clients
  - **Spatial variability**: signal strength depends on distance & location
  - **Temporal consistency**: good chance this will be true in days/weeks/months/...
- Map of "**radio fingerprints**" can be established



Fingerprint Positioning

Positioning with WiFi Fingerprint

- Collect Fingerprint $r = [\, r_1, r_2, \ldots, r_n]$
- Compute distance $||\, r_i - s \,||$ and position user at:
  - Nearest Neighbor (NN)
  - K Nearest Neighbors ($w_i = 1 \,/\, K$)
  - Weighted K Nearest Neighbors $(w_i = 1 \,/\, ||\, r_i - s \,||\,)$



$s = [\, -70, -51]$

NN, KNN, WKNN

RadioMap

$r_1 = [\, -71, -82, (x_1,y_1)]$

$r_2 = [\, -65, -80, (x_2,y_2)]$

…

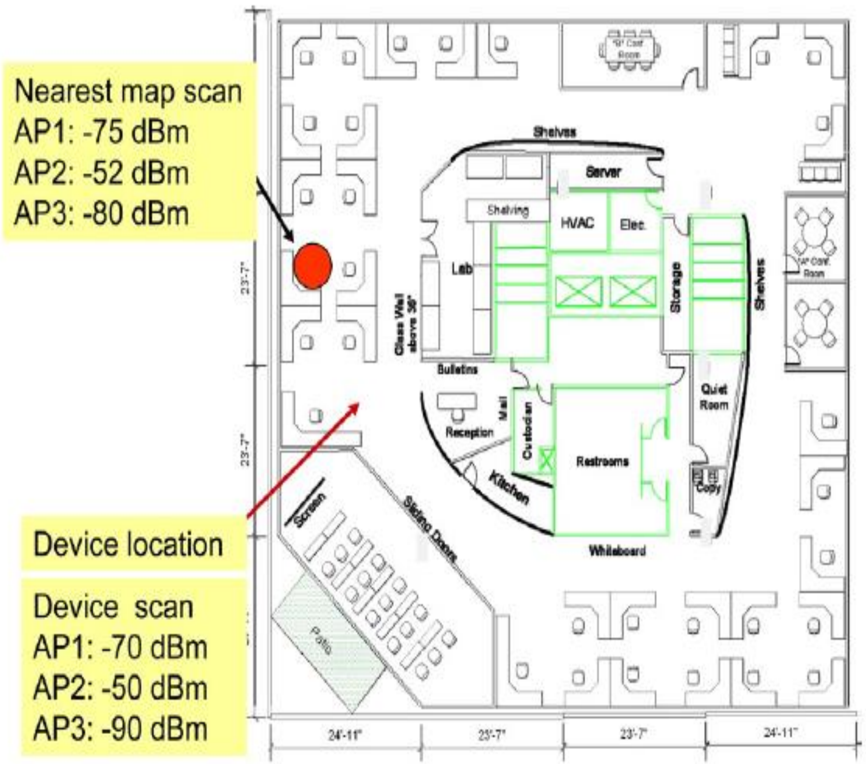
$r_N = [\, -73, -44, (x_N,y_N)]$

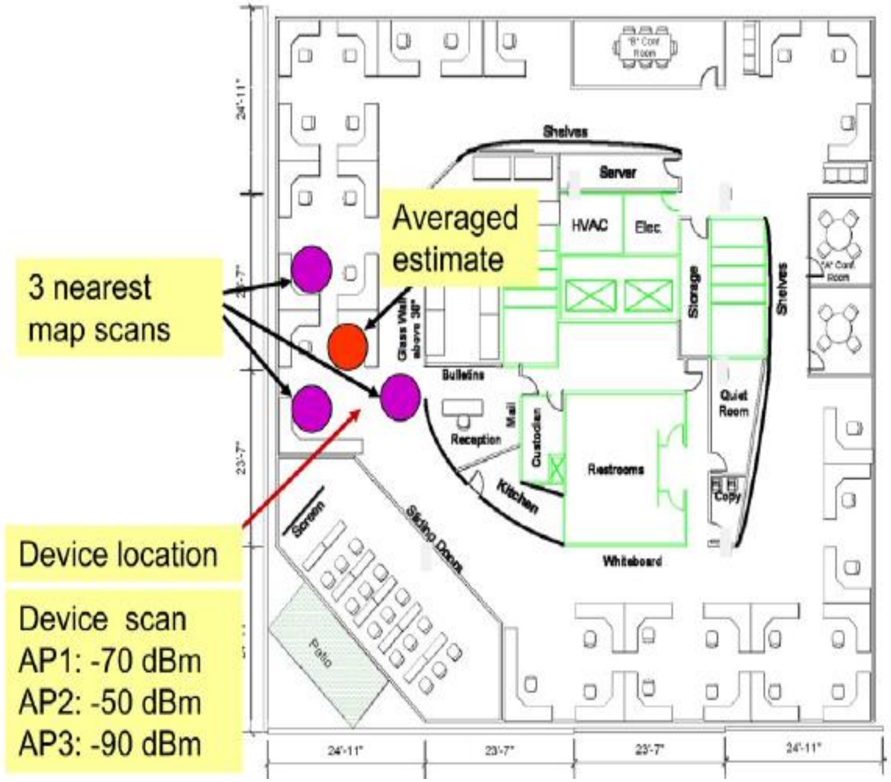
Fingerprint Positioning

Collected Fingerprints

Fingerprint Positioning

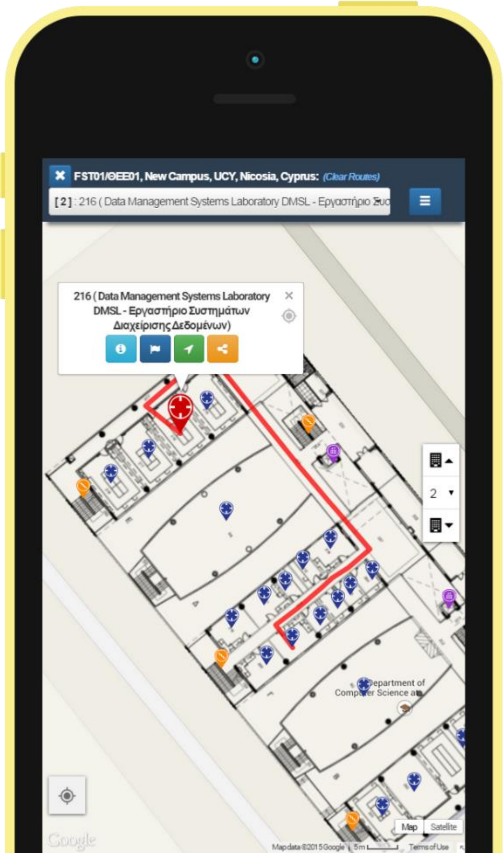
Compute distance and position user at Nearest Neighbor





Fingerprint Localization (Android)

- open-source implementation released called AnyPlace using WiFi signal
  http://anyplace.cs.ucy.ac.cy/



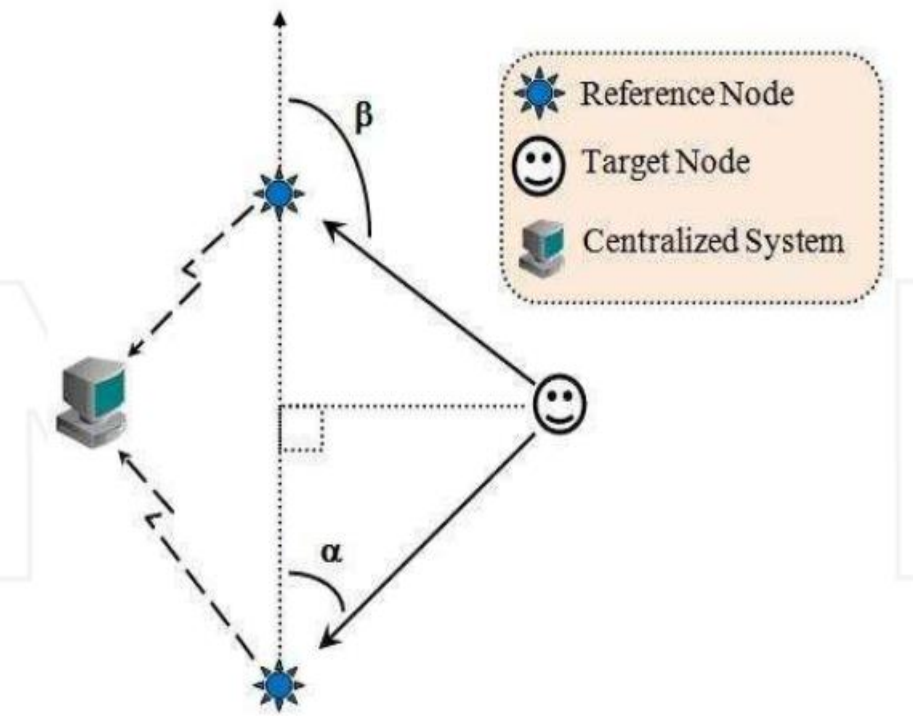
Wi-Fi Localization

- Position using Wi-Fi RSS Fingerprint
  - Indoor Wi-Fi positioning gives 2-3m accuracy
  - But requires **high calibration overhead**: 10+ hours per building
  - Changes over time (adding/removing/relocating APs) impact accuracy

Triangulation

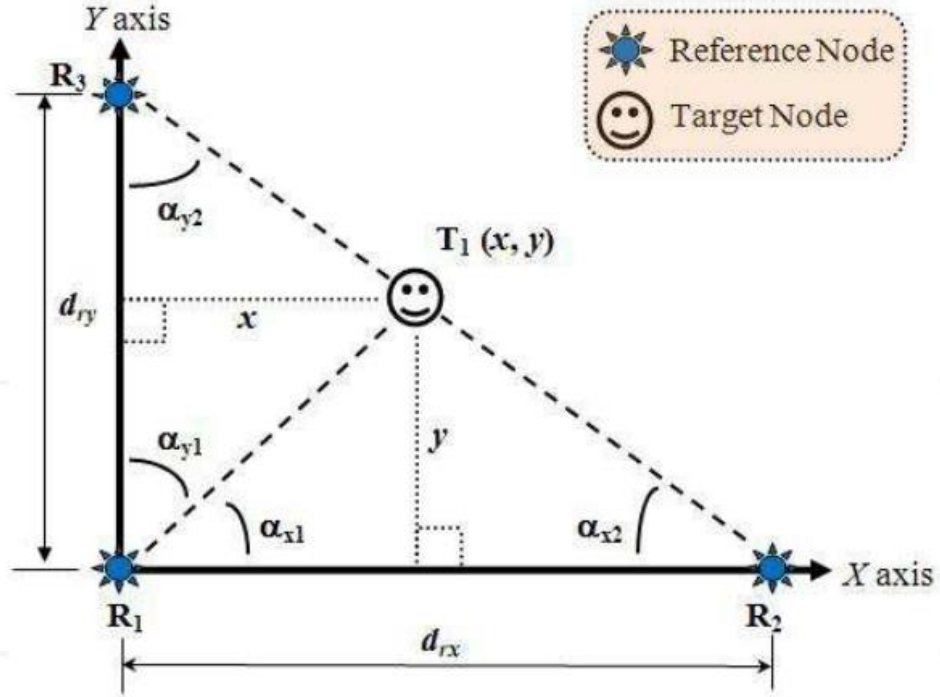
Target node triangulation

1. need direction finding hardware attached to sensor node
2. All reference node broadcast signals to target node
3. Target node computes its coordinate



Triangulation

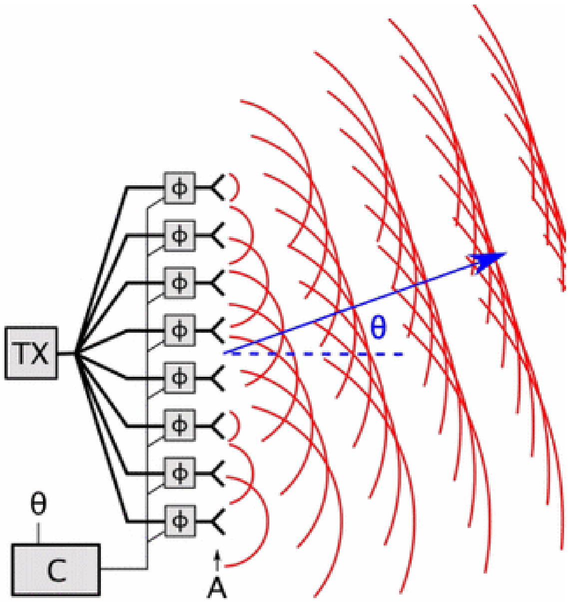
- Location determination based on two angles and a distance between them
- d_r measured and stored first
- (x, y) given by law of sines:



$$x = \frac{d_{ry}\sin(\alpha_{y1})\sin(\alpha_{y2})}{\sin(\alpha_{y1} + \alpha_{y2})}, y = \frac{d_{rx}\sin(\alpha_{x1})\sin(\alpha_{x2})}{\sin(\alpha_{x1} + \alpha_{x2})}$$

Other Ranging Techniques

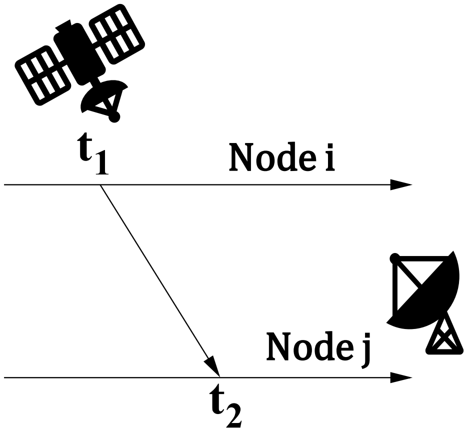
- Angle of Arrival (AoA) - direction of signal propagation
  - Typically achieved using an array of antennas (or receivers)
  - **Spatial separation of antennas** leads to differences in arrival times, amplitudes, and phases
  - Apply **triangulation** on angles between signal and some references
- Pros: accuracy can be high (within a few degrees)
- Cons: adds significant hardware cost



Time of Arrival Positioning (Revisited)

Time of Arrival (ToA, time of flight)

distance between sender and receiver of a signal can be determined using the measured signal propagation time and known signal velocity



- One-way ToA
  - one-way propagation of signal

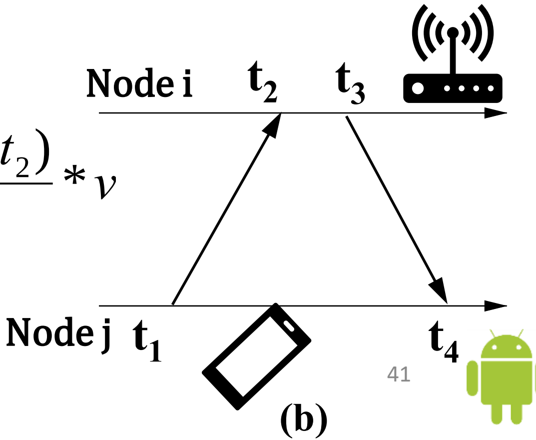
$$dist_{ij} = (t_2 - t_1) * v$$

  - requires highly accurate synchronization of sender and receiver clocks

- Two-way ToA
  - round-trip time of signal is measured at sender device

$$dist_{ij} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} * v$$

  - third message if receiver wants to know the distance



WiFi RTT Positioning

- WiFi RTT (Round Trip Time) /802.11mc
  - Introduced in Android 9 to enable supporting devices to measure a distance to other Access Points (APs) or Wi-Fi Aware peers
  - Still in its infancy, possibly to achieve **sub-meter accuracy**

Reference

1. Ad hoc positioning system (APS), IEEE GLOBECOM '01
   https://ieeexplore.ieee.org/document/965964?arnumber=965964

2. An Empirical Characterization of Radio Signal Strength Variability in 3-D IEEE 802.15.4 Networks Using Monopole Antennas
   http://link.springer.com/chapter/10.1007/11669463_24

3. WiFi positioning system (WiPS)
   https://en.wikipedia.org/wiki/Wi-Fi_positioning_system

4. Wi-Fi ranging with RTT | Android Developer Guide
   https://developer.android.com/guide/topics/connectivity/wifi-rtt

Appendix: Positioning Accuracy

Technique	Range / accuracy	Remarks
(A)GPS	Accuracy: 6.0 m - 10.0 m	+ Low barrier entry - Slow computation and processing time Very susceptible to reflectance and multi-paths
GSM / UMTS	Range: ≈ 35.0 km	+ Globally available - Cell-based accuracy
Bluetooth	Range: ≈ 100 m Accuracy:10 m – 20 m	+ High speed data transfer - Positioning via triangulation (no objects into account),Explicit links between devices required
IR	Range: 0.7 m – 2.5 m	- Short range of detection limits infrastructure, No penetration of materials / multipath, Line of sight, Signal can be disturbed easily
IEEE 802.11 (Wi-Fi)	Range: ≈ 32 m (indoor) ≈ 95 m (outdoor) Accuracy: 1 m – 5 m	+ Large scale available over the world .Economical viable - High power consumption, Slightly multipath susceptible