Sensor & Sensor Data Processing

Part I

Learning Objectives

- Characteristics of different types of signal sources and sensors
- Wireless
- IMU data processing
  - Device attitude
  - Step counting
- Camera

Sensor

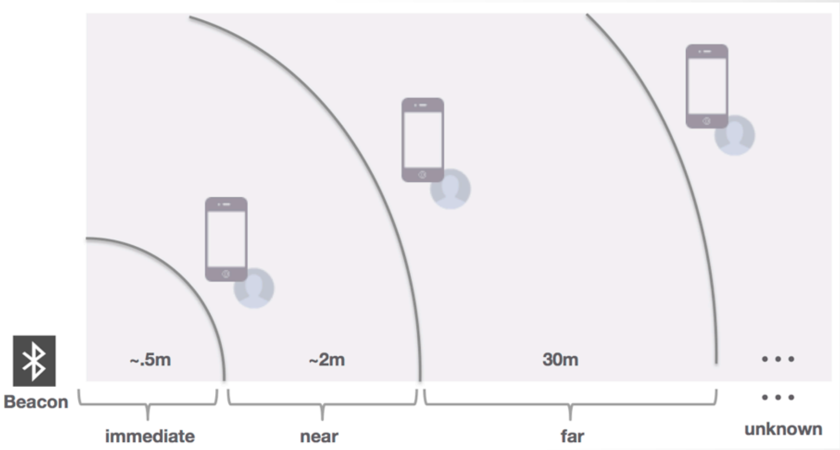
- Narrowly speaking, sensors are

> A device, such as a photoelectric cell, that receives and responds to a signal or stimulus – The Free Dictionary

- Examples of hardware sensors
  - Camera, photodiode, gyro, compass, accelerometer, temperature sensor, barometer, IR sensor, microphone, EEG, EMG, ECG, GPS,…, and WIRELESS NETWORK INTERFACES
- Today's mobile OS also offers software-based sensors that derive data from one or more hardware sensors
  - e.g., on Android, linear acceleration and orientation
- And, humans as sensors

Wireless Interfaces as Sensors

- Not such a radical idea
- Positioning
  - Global positioning system (GPS)
  - Cellular e-911
  - iBeacon
- Proximity
  - NFC
  - RFID
- Others
  - Motion detection
  - Gesture recognition



iBeacon for dummies

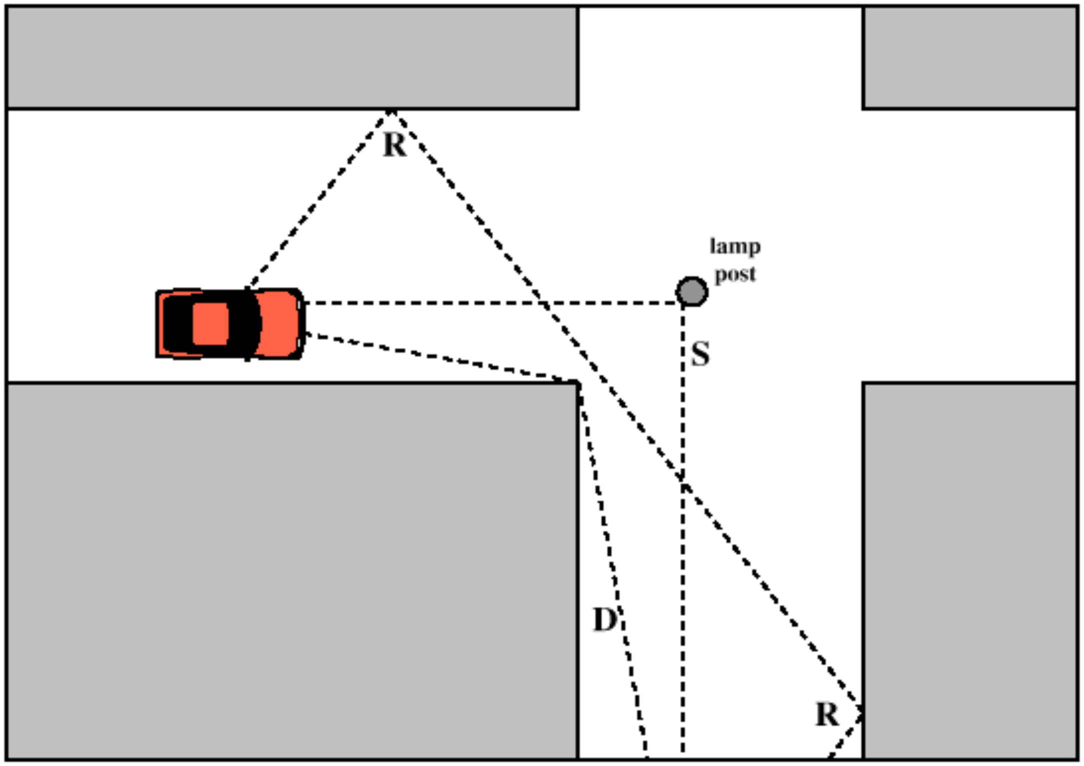
wisee

Whole-Home Gesture Recognition Using Wireless Signals

http://wisee.cs.washington.edu

Qifan Pu, Sidhant Gupta, Shyam Gollakota, Shwetak Patel

Wireless Sensors: Why, How and Limitations



$$\lambda = C / f$$

Ex: 3e8/2.4e9 = 12.5cm

R: reflection

D: diffraction -- a modification which light undergoes especially in passing by the edges of opaque bodies or through narrow openings

S: scattering -- obstacle << wave length

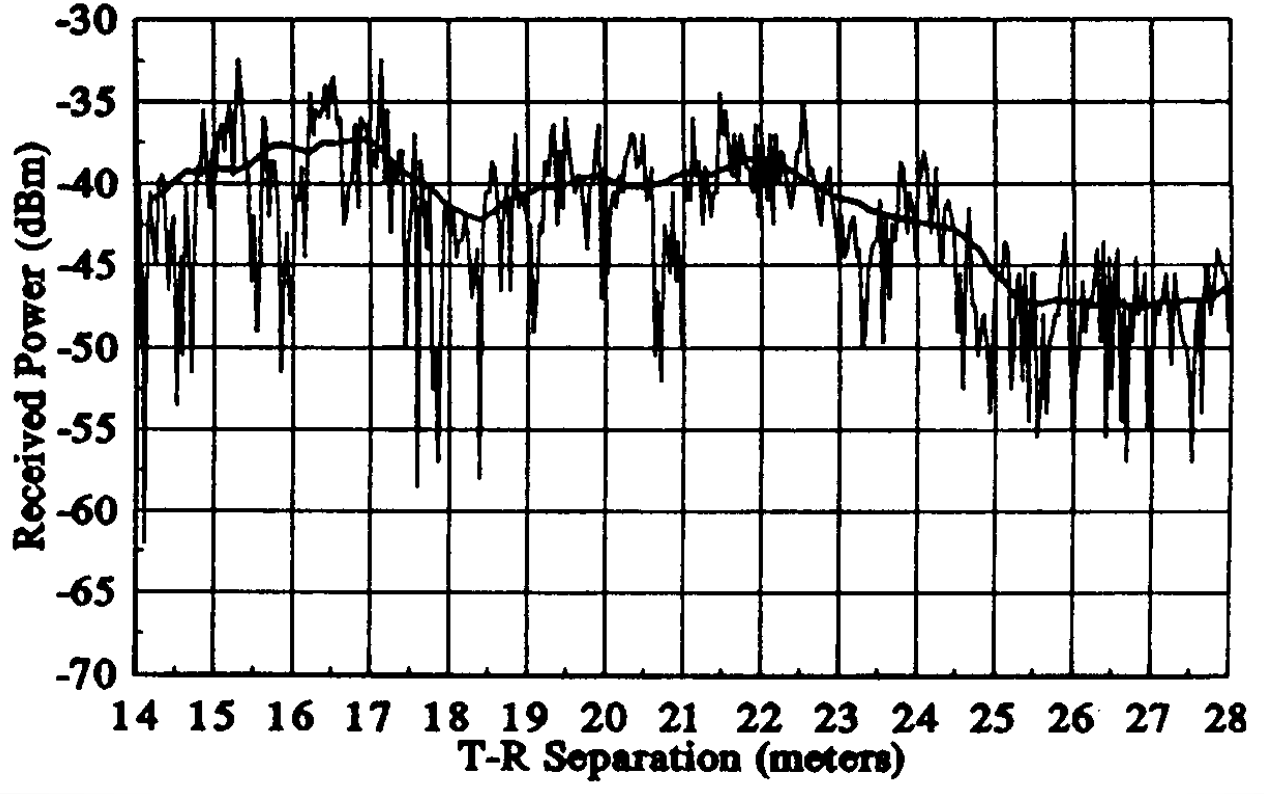
Wireless Link Characteristics

Differences from wired link ….

- decreased signal strength over distance: radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- multipath propagation: radio signal reflects off objects ground, arriving ad destination at slightly different times

… make communication across (even a point-to-point) wireless link much more "difficult"

Radio Propagation Models



How to characterize the signal at the receiver?

-Transmitter, receiver, environment, time

- Large scale, small scale

Propagation Models

- Large scale models predict behavior averaged over distances >> wave length λ=c/f
  - Function of distance & significant environmental features, roughly frequency independent
  - Breaks down as distance decreases
  - Useful for modeling the range of a radio system and rough capacity planning
- Small scale (fading) models describe signal variability on the scale of λ
  - Multipath effects (phase cancellation) dominate, path attenuation considered constant
  - Frequency and bandwidth dependent
  - Focus is on modeling "Fading": rapid change in signal over a short distance or length of time

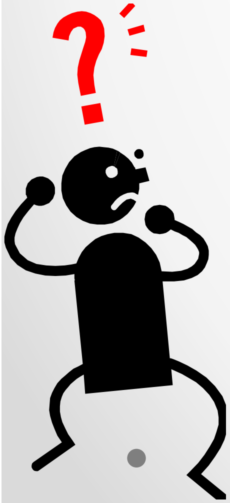
Large-scale Models

- Path loss models
    - Free space
    - Log-distance
    - Log-normal shadowing
- Outdoor models
    - "2-Ray" Ground Reflection model
    - Diffraction model for hilly terrain
- Indoor models

Free-space Path Loss Model

- Friis free space equation:
  - G_t, G_r are the antenna gains at the transmitter and receiver
  - λ is the wavelength
  - d is the distance
  - L is a loss factor not related to propagation
  - Transmission power Pt
  - Received power

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



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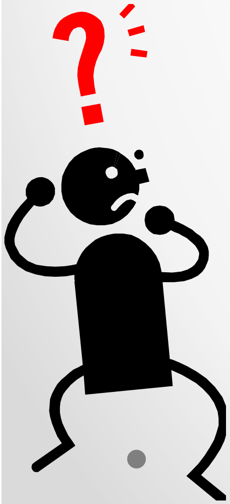
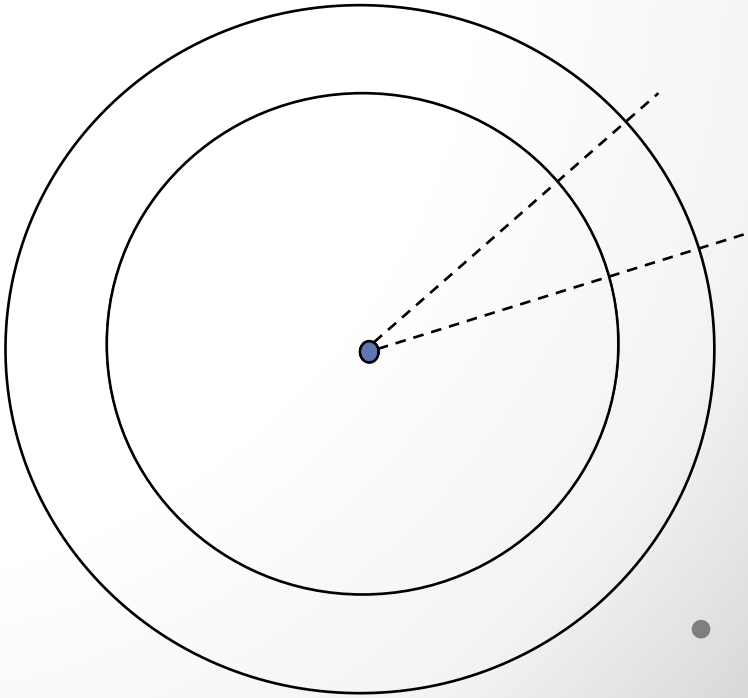


$$E_r(f,t) = \frac{\alpha \cos 2\pi f(t - d/c)}{d}$$

$$P_r(d) \propto E_r^2(f,t)$$



Free Space Model

- Path loss $P_r(d) = P_r(d_0)(\frac{d_0}{d})^2, d \geq d_0 \geq d_f$

$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

- Only valid beyond far-field distance

$$d_f = \frac{2D^2}{\lambda}$$

, where D is the transmit antenna aperture

$$d_f >> D, d_f >> \lambda$$

dB = 10 log(P2/P1), use to represent power ratio; P1 is called the power reference.

dBm indicates dB refers to P1 = 1mW

dBW indicated dB refers to P1 = 1W

Example: 0dBW = 1W = 30dBmW = 1000mW

Example

- Far field distance for an antenna with maximum dimension of 1m and operating freq of 900MHz

$$d_f = \frac{2D^2}{\lambda} = \frac{2}{3\times 10^8 / 900\times 10^6} = 6m$$

- Consider a transmitter producing 50w of power and with a unity gain antenna at 900MHz. What is the received power in dBm at a free space distance of 100? What about 10Km? (assume L =1)

$$P_t = 10\log(50\times 10^3) = 47dBm$$

$$P_r(100) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = 3.5\times 10^{-3} mW = -24.5dBm$$

$$P_r(10km) = -24.5 - 20\log(100) = -64.5dBm$$

Log-distance Path Loss Model

- Log-distance generalizes path loss to account for other environmental factors

$$\boxed{PL(d)[dB] = PL(d_0) + 10\beta \log(d / d_0)}$$

  - Choose a d_0 in the far field.
  - Measure $PL(d_0)$
  - Take measurements and derive β empirically

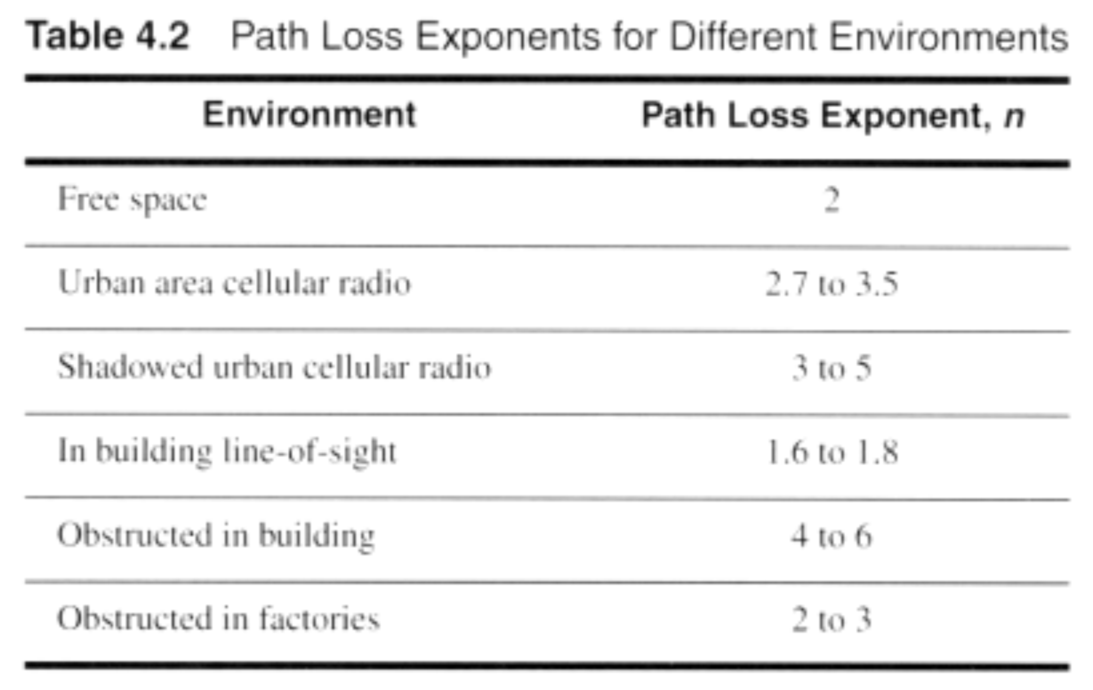


Table 4.2 Path Loss Exponents for Different Environments

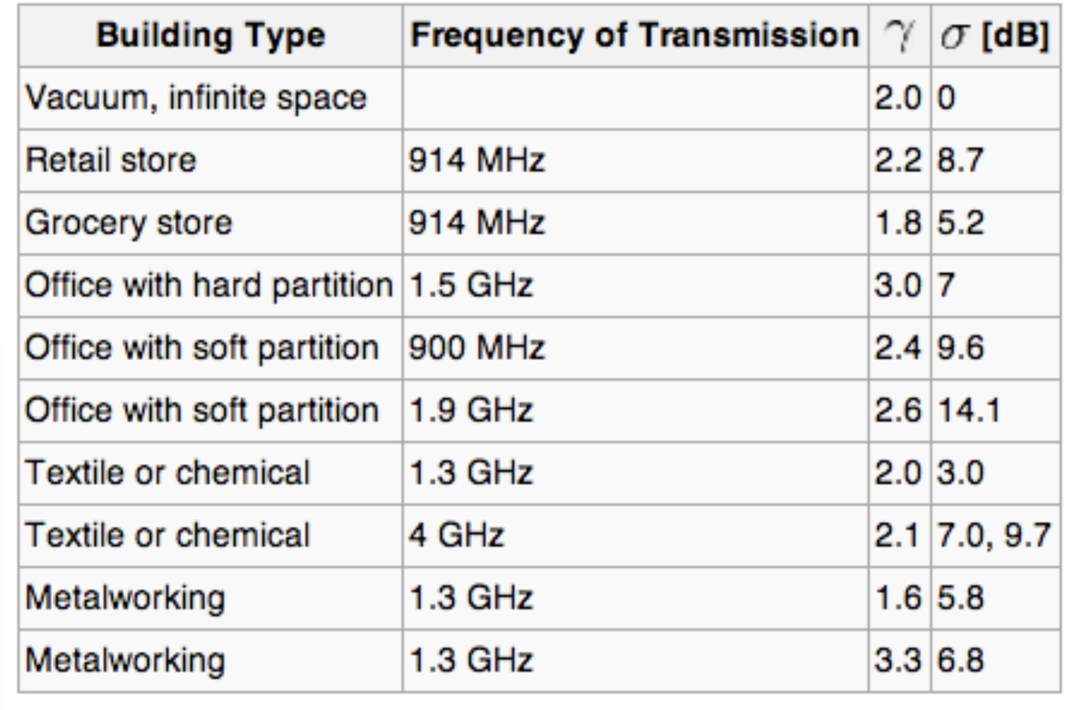
Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Log-normal Shadowing

- Shadowing occurs when objects block light of sight (LOS) between transmitter and receiver

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10\beta\log(\frac{d}{d_0}) + X_\sigma$$

X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB)

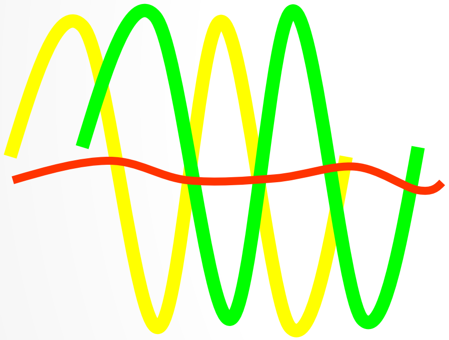


Building Type	Frequency of Transmission	γ	σ [dB]
Vacuum, infinite space		2.0	0
Retail store	914 MHz	2.2	8.7
Grocery store	914 MHz	1.8	5.2
Office with hard partition	1.5 GHz	3.0	7
Office with soft partition	900 MHz	2.4	9.6
Office with soft partition	1.9 GHz	2.6	14.1
Textile or chemical	1.3 GHz	2.0	3.0
Textile or chemical	4 GHz	2.1	7.0, 9.7
Metalworking	1.3 GHz	1.6	5.8
Metalworking	1.3 GHz	3.3	6.8

Small-scale Fading

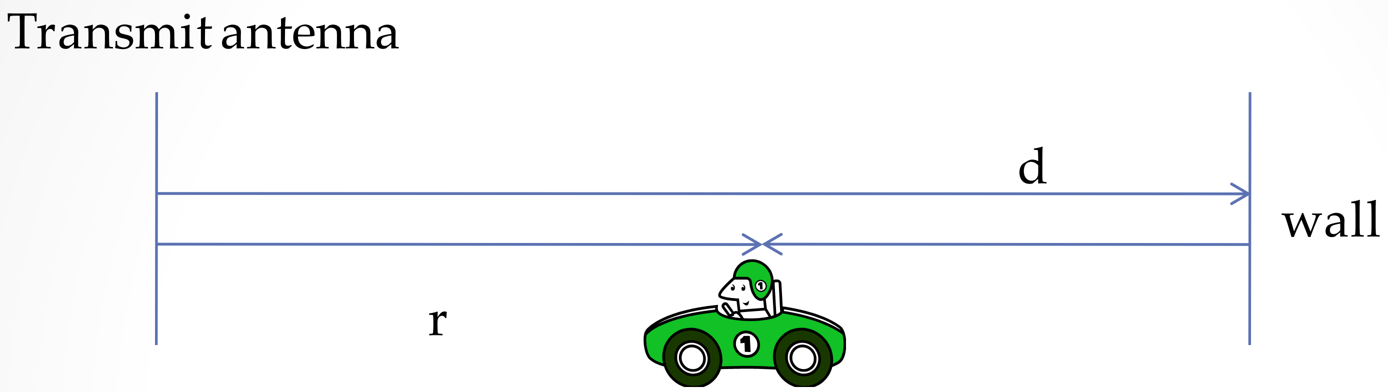
- Factors that contribute to small-scale fading
  - Multi-path propagation -- phase cancellation etc.
  - Speed of the mobile -- Dopler effect
  - Speed of surrounding objects
  - The transmission bandwidth of the signal wrt bw of the channel

Multipath Causes Phase Difference



Green signal travels 1/2λ farther than Yellow to reach receiver, who sees Red.
For 2.4 GHz, λ (wavelength) =12.5cm.

Reflecting wall, fixed antenna



$$E_r(f,t) = \frac{\alpha \cos 2\pi f(t - r/c)}{r} - \frac{\alpha \cos 2\pi f(t - (2d - r)/c)}{2d - r}$$

Phase difference: $\Delta\theta = \frac{4\pi f}{c}(d - r) + \pi$

Doppler Shift

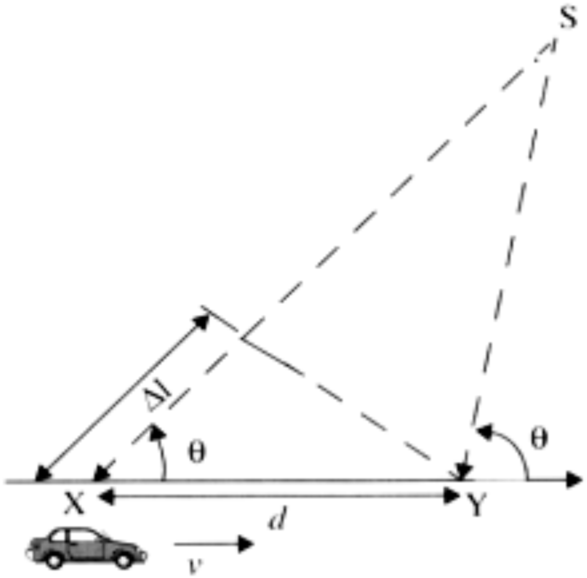
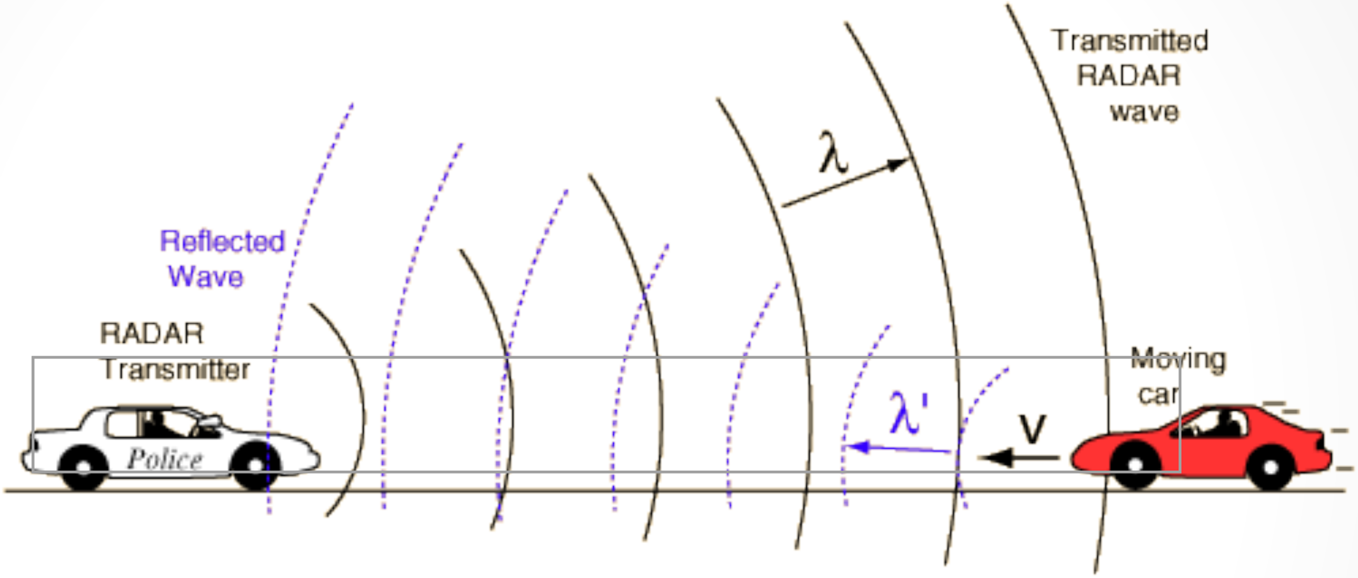


Figure 5.1 Illustration of Doppler effect.

$$E_r(f,t) = \frac{\alpha \cos 2\pi f \left(t + \frac{v\cos\theta}{c} t + t_0\right)}{r}$$

$$f' = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = f + \frac{v}{\lambda}\cos\theta, f_d = \frac{v}{\lambda}\cos\theta$$

Example: Police Radar



$$f_{reflected} - f_{transmitted} = \Delta f = \frac{2v_{target}}{\lambda}$$

$$f = 900MHz, \lambda = 0.333m, v = 60Km/hr$$

$$\Delta f = 100Hz$$

Statistical Fading Models

- Fading models model the probability of a fade occurring at a particular location
  - Used to generate an impulse response
  - In fixed receivers, channel is *slowly* time-varying; the fading model is reevaluated at a rate related to motion
- Rayleigh fading distribution
  - Models a flat fading signal
  - Used for individual multipath components

$$p(r) = \frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2})$$

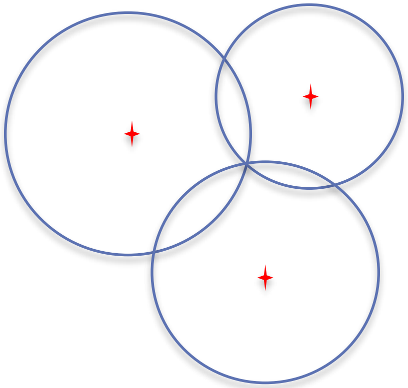
- Ricean fading distribution
  - Used when there is a dominant signal component, e.g. LOS + weaker multipaths
  - parameter K (dB) defines strength of dominant component; for K=-∞, equivalent to Rayleigh

Wireless Sensors Can …

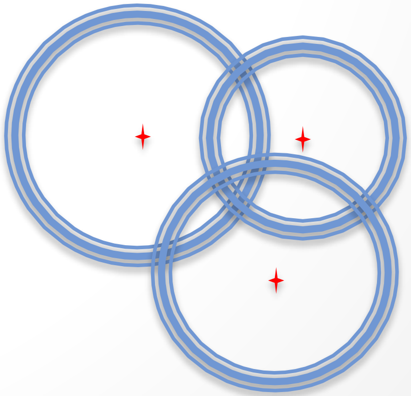
- Positioning
  - Global positioning system (GPS)
  - Cellular e-911 ✔
  - iBeacon ✔
- Proximity
  - NFC
  - RFID
- Others
  - Motion detection ✔
  - Gesture recognition

Trilateration with Wireless Signals

- If we know distances to known anchors (e.g, WLAN APs, cellular tower) exactly
  - Trilateration → location in 2D

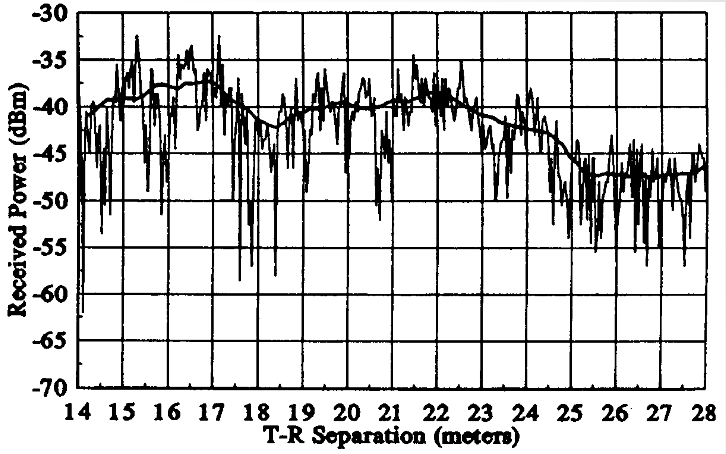


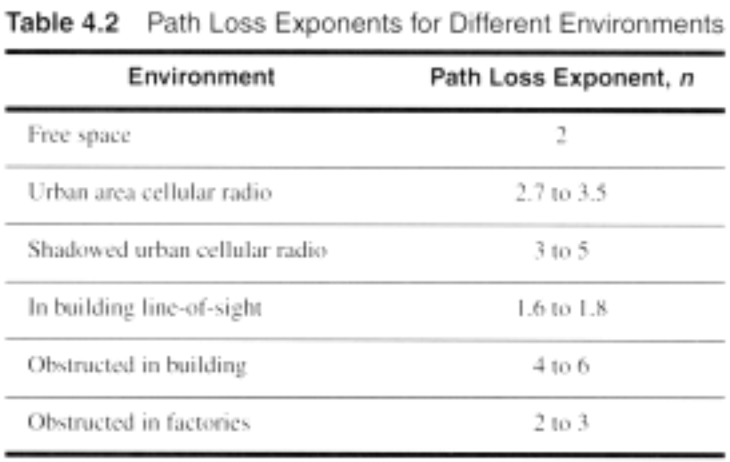
- In reality,
  - Anchors location may not be known exactly
  - No actual ranging measurements
    - Instantaneous measurements fluctuate
    - Path loss exponent unknown/changes
    - Antenna gain not known
  - The circles may not intersect



Solution Ideas (I)

- Anchors location may not be known exactly
  - Simultaneous mapping and location(SLAM)
  - Use fingerprinting based approaches
- Instantaneous measurements fluctuate
  - Averaging over multiple measurements
- Path loss exponent unknown/changes
  - Estimation from the table
  - Field experiments
  - Ray tracing





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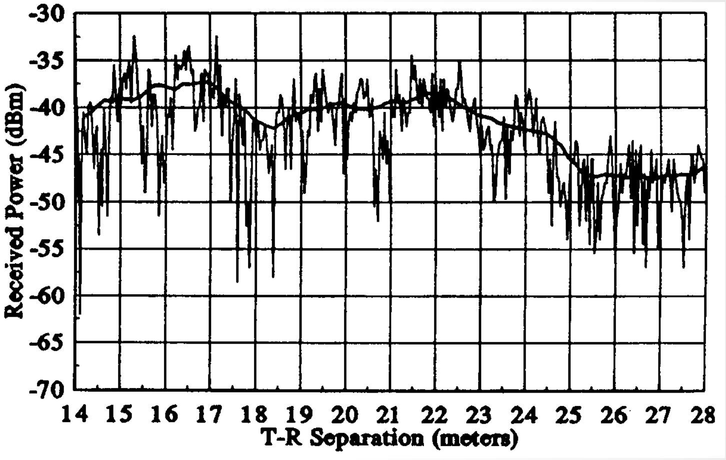
$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10\beta\log(\frac{d}{d_0}) + X_\sigma$$

Solution Ideas(II)

- Antenna gain unknown
  - Treat as a variable to solve
  - Subtract out
- The circles may not intersect
  - Minimizing square errors

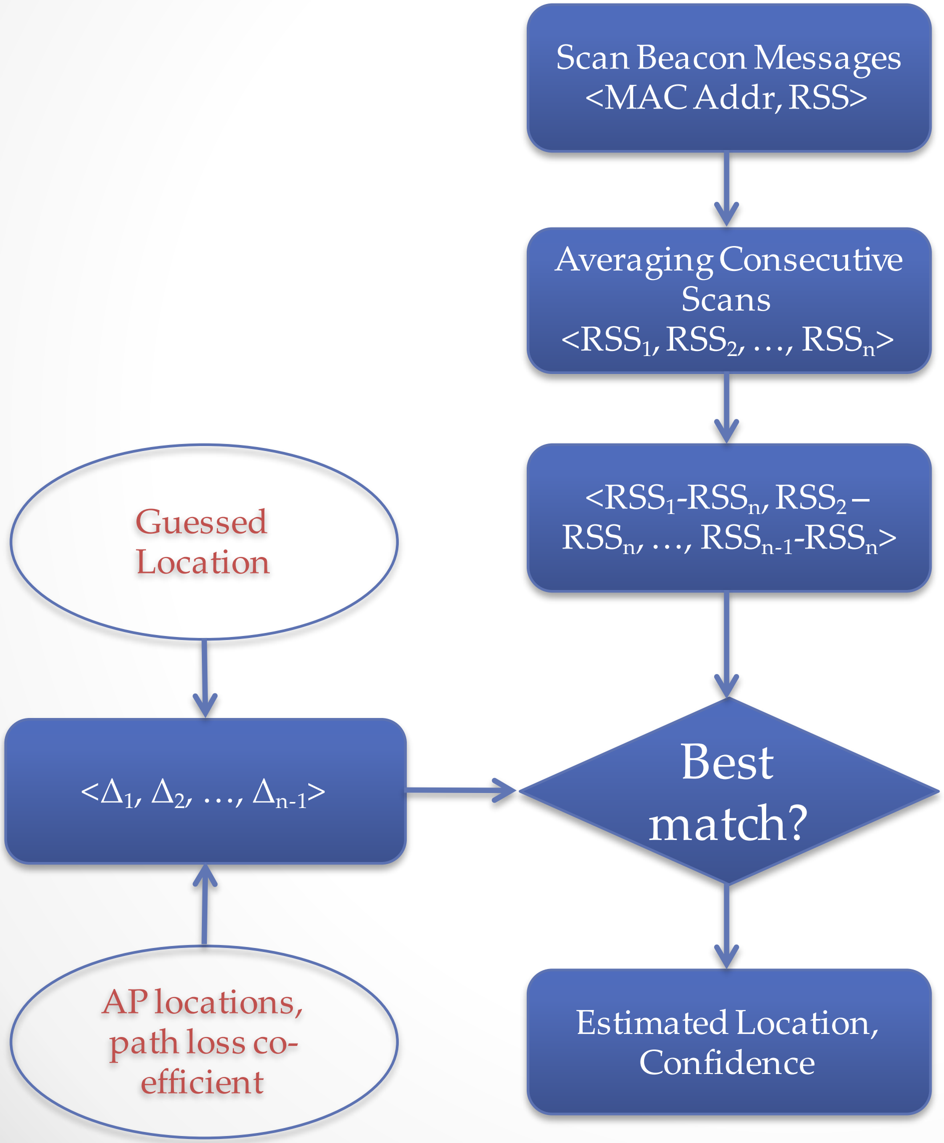
$$\arg_{\hat{x},\hat{y}} min\left(\left(d_1-\sqrt{(x_1-\hat{x})^2+(y_1-\hat{y})^2}\right)^2+\left(d_2-\sqrt{(x_2-\hat{x})^2+(y_2-\hat{y})^2}\right)^2 + (d_3-\sqrt{(x_3-\hat{x})^2+(y_3-\hat{y})^2})^2\right)$$



where d1, d3, d3 are distances estimation from the path loss model, (x1, y1), (x2, y2), (x3, y3) are the anchor locations

  - Can implement using an exhaustive search

Algorithm Sketch (WiFi)


Scan Beacon Messages <MAC Addr, RSS>

Averaging Consecutive Scans $<RSS_1, RSS_2, \ldots, RSS_n>$

$<RSS_1 - RSS_n, RSS_2 - RSS_n, \ldots, RSS_{n-1} - RSS_n>$

Guessed Location

AP locations, path loss co-efficient

$<\Delta_1, \Delta_2, \ldots, \Delta_{n-1}>$

Best match?

Estimated Location, Confidence

Note: need to distinguish virtual APs

Remove effects of antenna gains

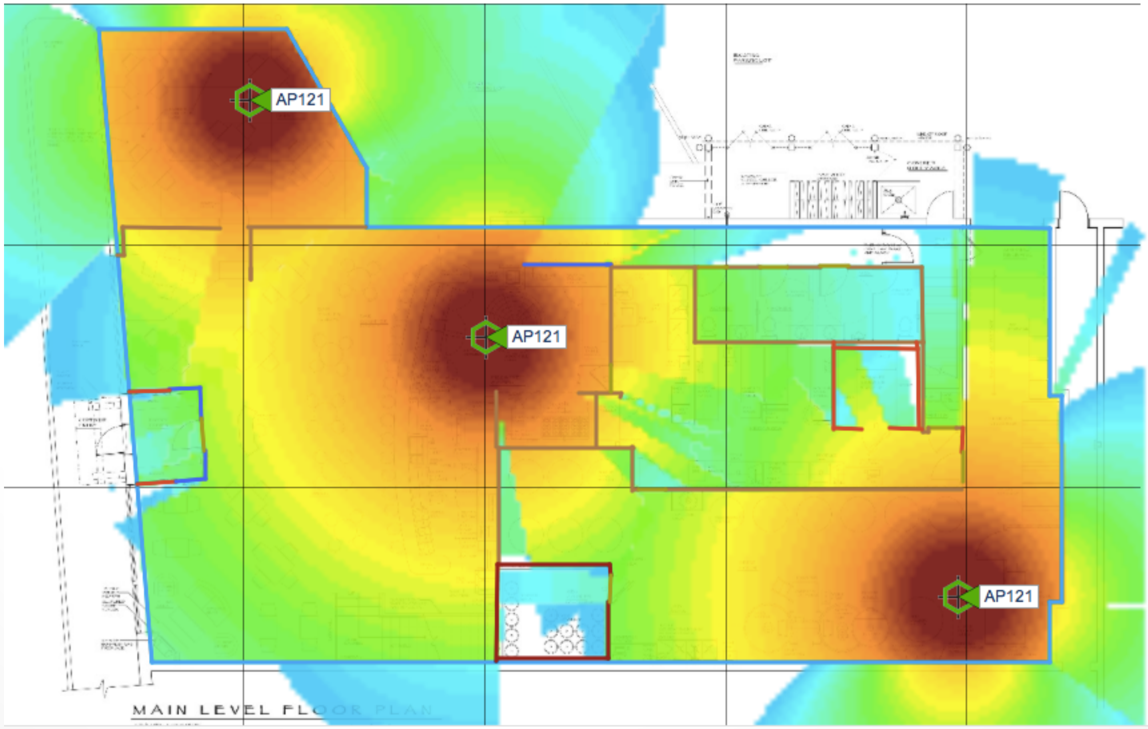
Confidence can be computed using the log-normal model assuming independent distributions

In Practice

- Signal propagation depends on many factors
  - Movement
  - Body blockage
  - …
- RSS itself is a coarse grained measurement – averaging over the entire bandwidth (e.g., 20MHz in 802.11a/b/g)
- Wireless signal trilateration cannot provide fine-grained location
  - "Immediate, near, far" in iBeacon positioning explained

Wireless Fingerprinting

- Trilateration approaches face difficulties in 1) locations of APs, and 2) RSS not a good measure for distance
- Alternatively, we can treat wireless signal propagation as a blackbox and associate RF signal measurements as "fingerprints" at locations



Algorithm Sketch (WiFi)

Site Survey

Training

Model

f^{-1}: FP->

<x,y, z>

Location

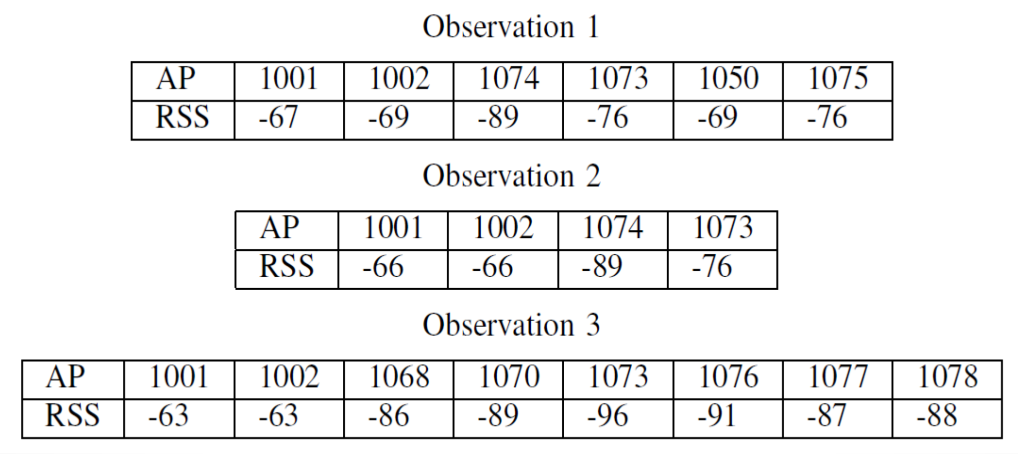
new RSS readings

Implementation notes:

- For both the site survey and online phases, need to take averages of multiple RSS readings respective to the same AP
- Can use $<\Delta_1, \Delta_2, \ldots, \Delta_{n-1}>$ as fingerprints to mitigate device heterogeneity

Implementation Notes

- The training phase:
  - Can be as simple as just setting up a lookup table
  - Or, performing regression/function fitting to derive the mapping f: <x, y,z> → FP (more on regression later)
- In the online phase,
  - Table lookup
  - Solving an optimization problem or using an exhaustive search
  - Be aware of missing AP data



Observation 1

AP	1001	1002	1074	1073	1050	1075
RSS	-67	-69	-89	-76	-69	-76

Observation 2

AP	1001	1002	1074	1073
RSS	-66	-66	-89	-76

Observation 3

AP	1001	1002	1068	1070	1073	1076	1077	1078
RSS	-63	-63	-86	-89	-96	-91	-87	-88

Incomplete data

Distance/Similarity Function

- Given two RSS vectors (in dB or dBm) A, B
- How similar are those two vectors
  - Euclidean distance, L1 norm
  - Cosine similarity

$$\text{similarity} = \cos(\theta) = \frac{A \cdot B}{\|A\|\|B\|} = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n} (A_i)^2} \times \sqrt{\sum_{i=1}^{n} (B_i)^2}}$$

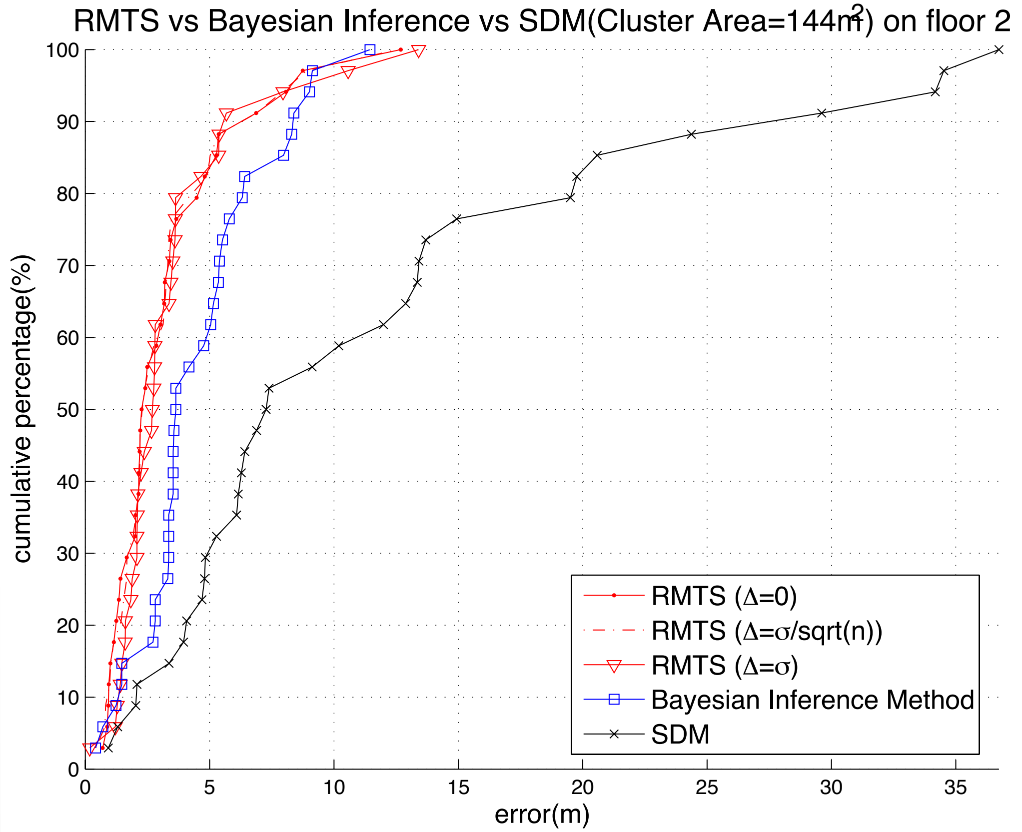
  - Tanimoto similarity

$$f(A,B) = \frac{A \cdot B}{|A|^2 + |B|^2 - A \cdot B}$$

- Dealing with missing elements: put -90dBm

Limitations

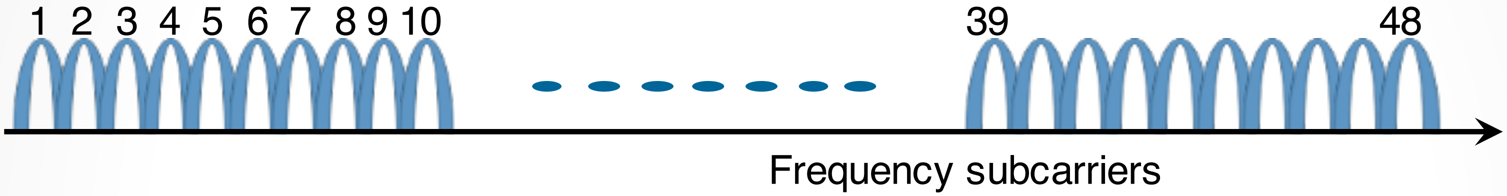
- Due to the variation and the coarse granularity of RSS
- Average location error 2 – 3 meter, possibly heavy tail



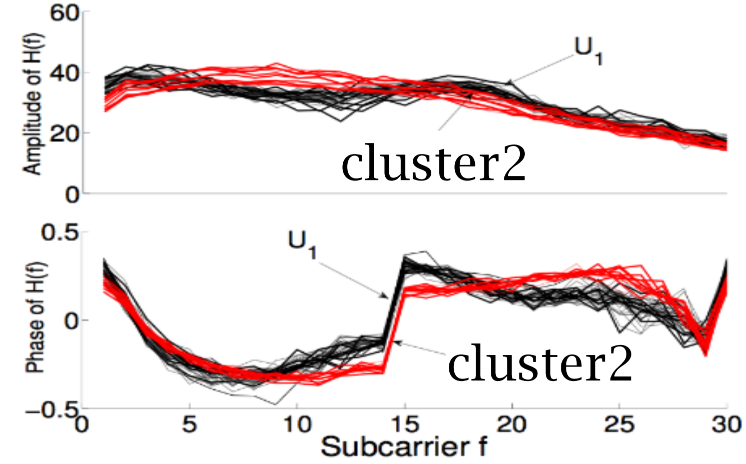
- Muqsith Mohammad, Rong Zheng, Ricard Barton, "Location Sensing with Robust Minimax Thin-Plate Splines", Allerton Conference on Communication, Control and Computing, 2006

Fine-grained RF Fingerprints

- 802.11 a/g/n implements OFDM
    - Wideband channel divided into subcarriers



- Intel 5300 card exports frequency response per subcarrier



Higher resolution
but higher variability too

Sen, S., Radunovic, B., Choudhury, R. R., Minka, T., "You are facing the Mona Lisa: Spot Localization Using PHY Layer Information", *MobiSys 2012*

Motion Detection

- Channel state information (CSI) may not be suitable for indoor positioning but can be useful in motion detection and gesture recognition
  - Presence, movement of people in the environment
  - Changes in gesture/posture
- Can be used in device free scenarios (also called radio tomographic)

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Take-home Messages

- RF signal power/phase → Channel → position (device-based), motion, gesture (device-free)
- Didn't cover direct time of flight (ToF), angle of arrival (AoA) based methods
  - GPS
  - WiZ
- Compared to visible lights and IR, no need for line of light in RF is both a curse and a bless
  - Can be used to detect motion behind walls
  - Signal propagation is not easily confined
- Issues that will be addressed in later part of the course
  - Movement is more than a collection of positions -- Bayesian filtering
  - Moved or not? How many people? -- Classification

Further Reading

- T S Rappaport, Chapter 4, Wireless Communications Principles And Practice