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The Use of Wireless Signals for Sensing and Interaction

Ubiquitous Computing Seminar FS2014

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Overview

- Gesture Recognition
- Classical Role of Electromagnetic Signals
- Physical Properties of Electromagnetic Signals
- Research Projects bridging wireless communication with computer interaction
  - Wi-Vi
  - WiSee
  - WiTrack
  - AllSee

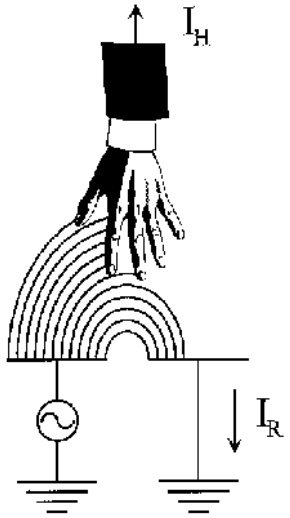
Beyond Classic Interfaces

- *„In the 21st century the technology revolution will move into the everyday, the small and the invisible…“*
  Mark Weiser

Image Source: Microsoft Wireless Laser Desktop 7000

Gesture Recognition

- Gestures as natural way of interaction
  - Vision based
  - Infrared based
  - Electric field sensing
  - Ultrasonic
  - Wearable sensors
  - Wireless signals



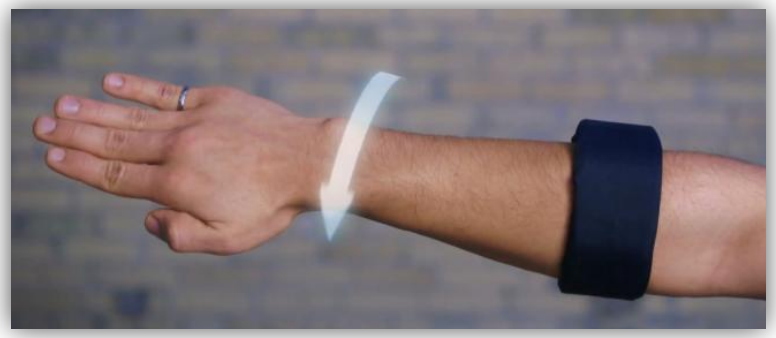
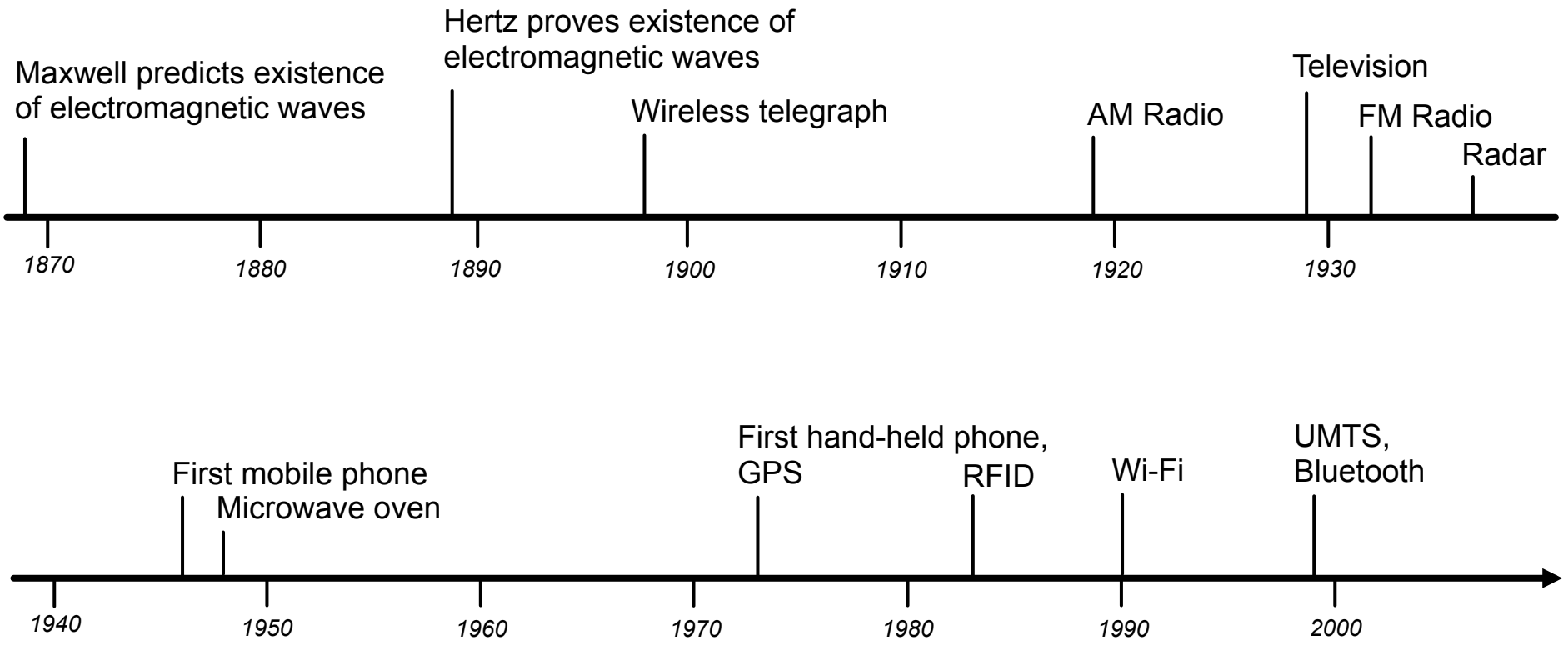


Image Sources: Microsoft Kinect; CHI '95; GetMYO.com

Why Wireless Signals for Gesture Recognition?

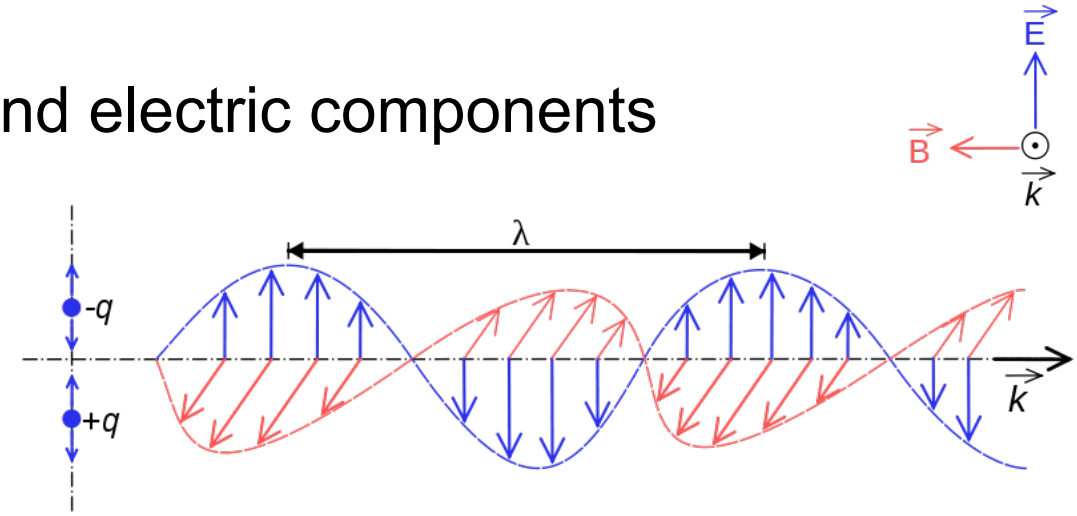
- Works without line-of-sight and through walls
  - Larger areas can be covered
  - Unseen gestures can be detected
- Independent of light conditions
  - Works day and night, indoors and outdoors
- Infrastructure already widely deployed
  - Wireless signals are all around us
  - Devices have wireless interfaces anyway
  - (Almost) no new hardware needed
- Relatively low power consumption

Classical Role of Electromagnetic Signals



Electromagnetic Signals

- Form of energy, emitted from a source
- Propagating via photon wave particles through space at the speed of light
- Oscillating magnetic and electric components
- Described by either
  - Wavelength λ
  - Frequency f
  - Energy E



$$E = hf = \frac{hc}{\lambda}$$

h = Planck's constant
c = speed of light

Image Source: Wikipedia

Electromagnetic Spectrum

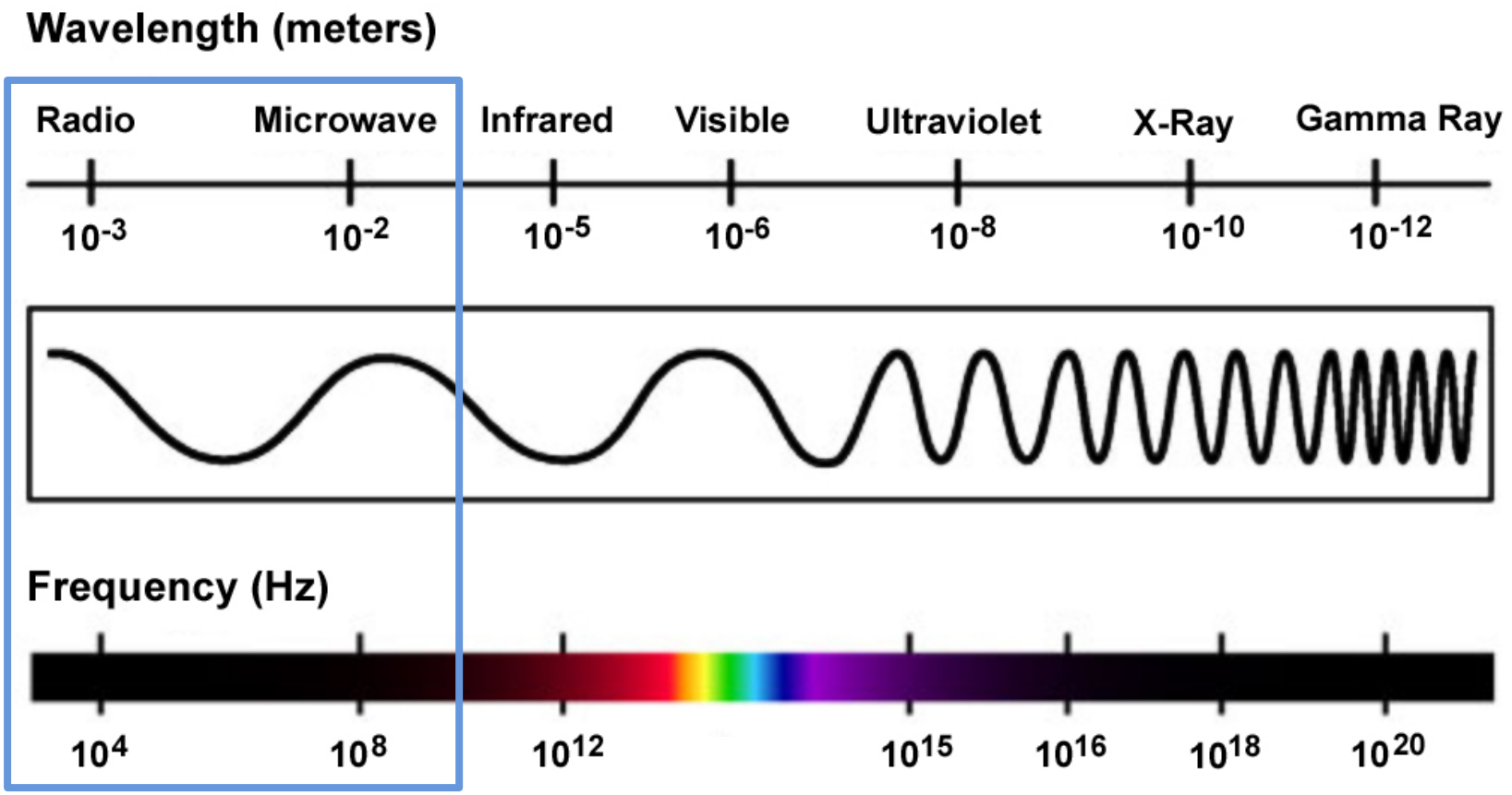
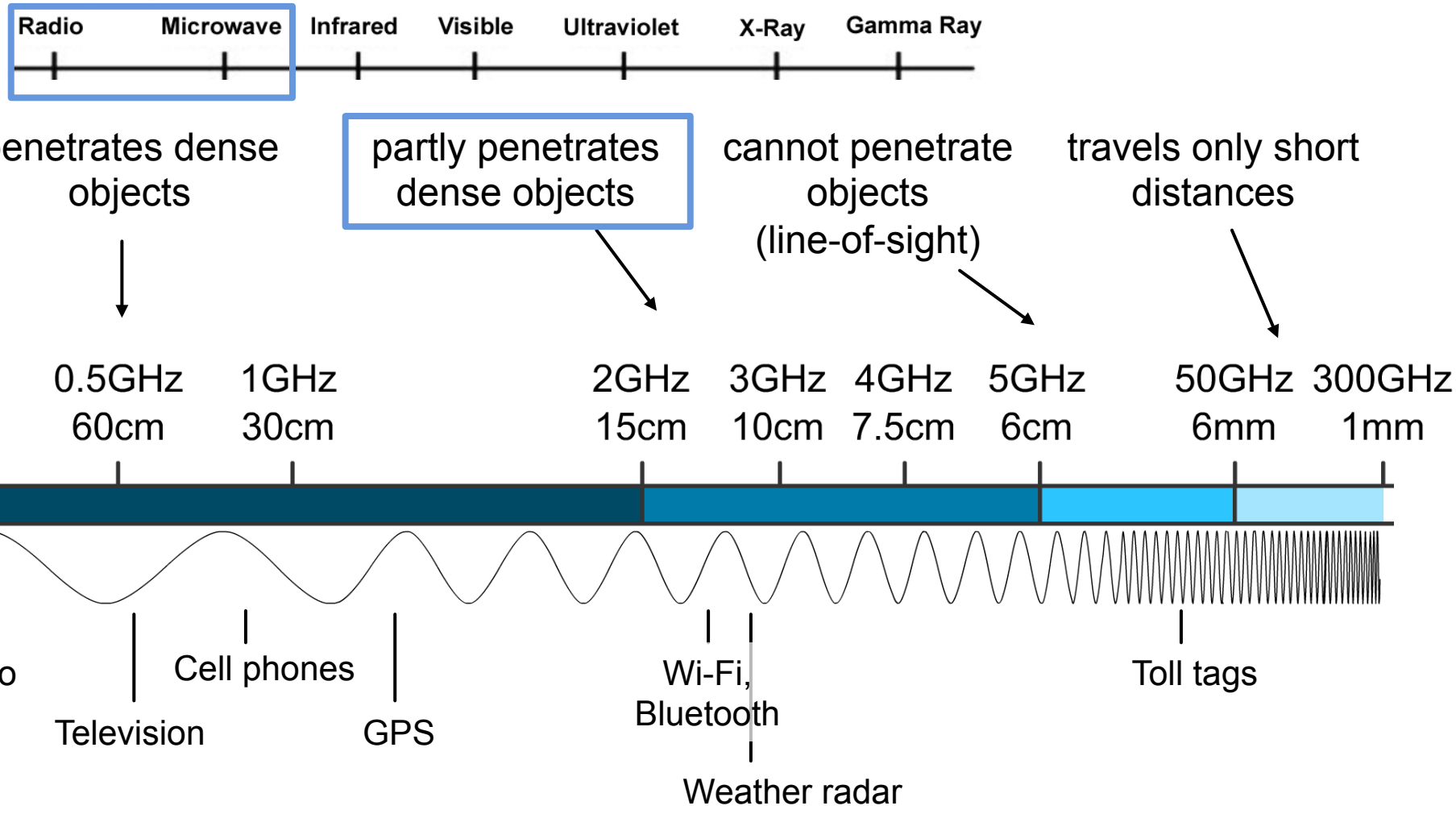


Image Source: University of Oregon

Radio (and Microwave) Spectrum



Source: New America Foundation

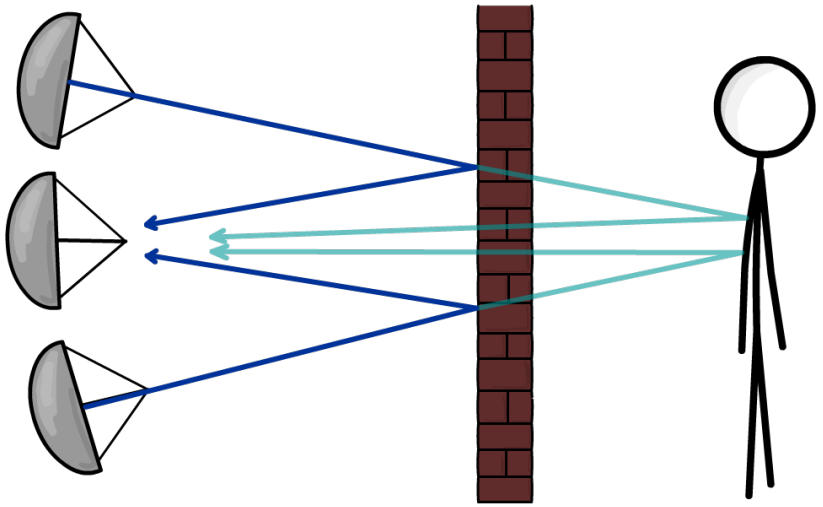
Research Projects

- "Wi-Vi"
  - Detect number of humans in a (closed) room and their relative movements
  - Communication through simple gestures
- „WiSee"
  - Recognize gestures in entire home, especially in non-line-of-sight scenarios
- „WiTrack"
  - 3D tracking of humans and body parts
- „AllSee"
  - Recognize gestures with almost negligible power

Wi-Vi : „See Through Walls with Wi-Fi!”

- “Wi-Fi Vision”
- Wi-Fi signals traverse wall and reflect off human bodies back to receiver

- 1 receive and 2 transmit directional antennas
- 20 MHz-wide Wi-Fi channel in the 2.4 GHz band



[Adib2013]

Applications for Wi-Vi

- Law enforcement
- Intrusion detection
- See through rubble in emergency situations
- Occupancy detection to control heating/light
- Entertainment

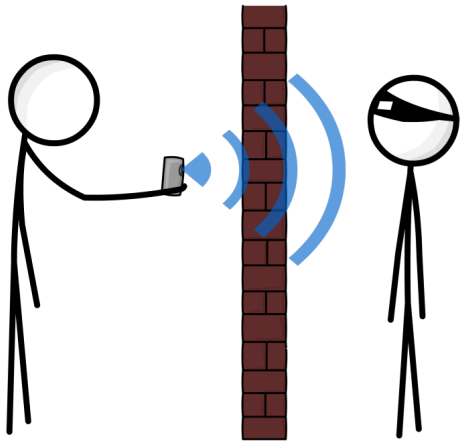
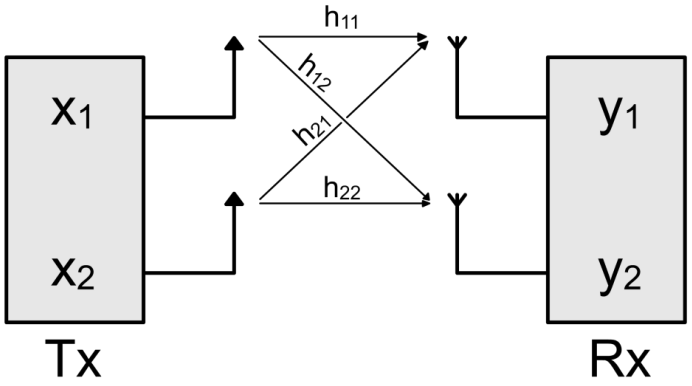


Image Source: Dartmouth College

MIMO (Multiple-Input Multiple-Output)

- Multiple antennas to improve throughput

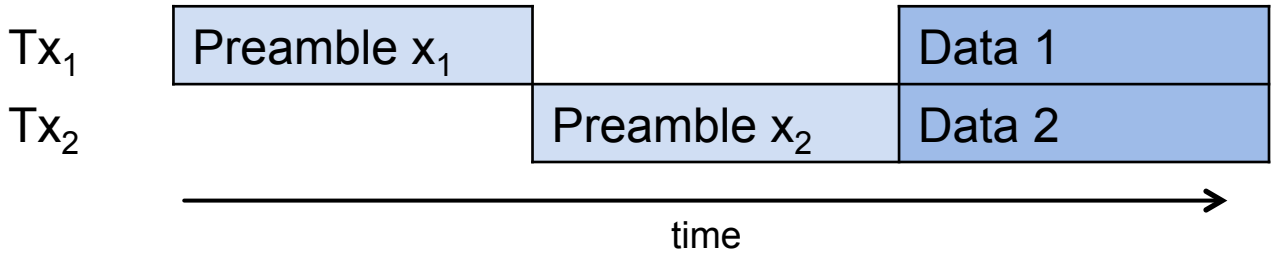


$$y_1 = h_{11}x_1 + h_{21}x_2$$
$$y_2 = h_{12}x_1 + h_{22}x_2$$

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \underbrace{\begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}}_{Channel\ matrix\ H} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

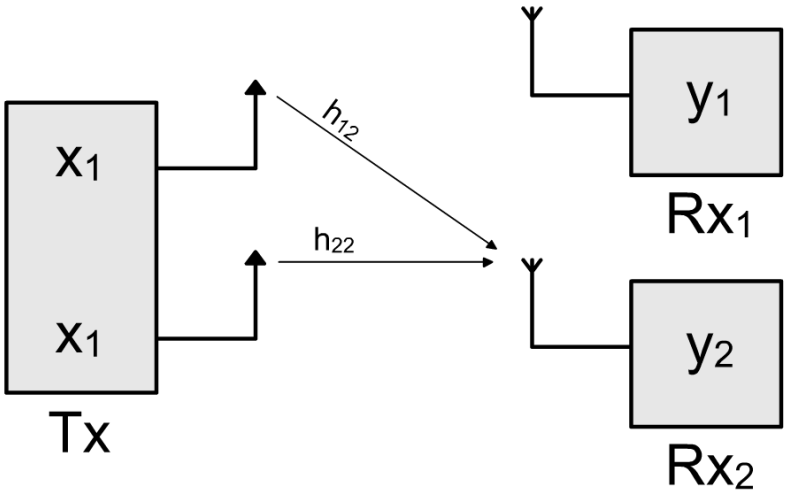
$$\vec{y} = H\vec{x} \xrightarrow[if\ H\ known\ and\ invertible]{} H^{-1}\vec{y} = \vec{x}$$

- Channels are estimated by sending known preamble from each transmitter in sequence



MIMO: Interference Nulling

- Each transmitter uses second antenna to null its transmission at the other receiver



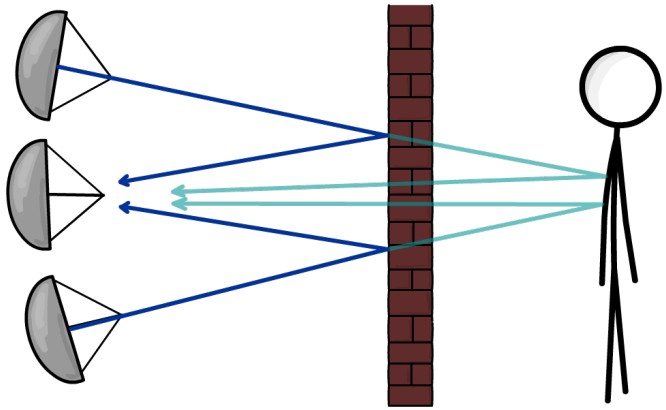
Instead of sending x_1
send $h_{22}x_1$ and $-h_{12}x_1$

$$y_2 = h_{12}(h_{22}x_1) + h_{22}(-h_{12}x_1) = 0$$

Dealing with the Flash Effect

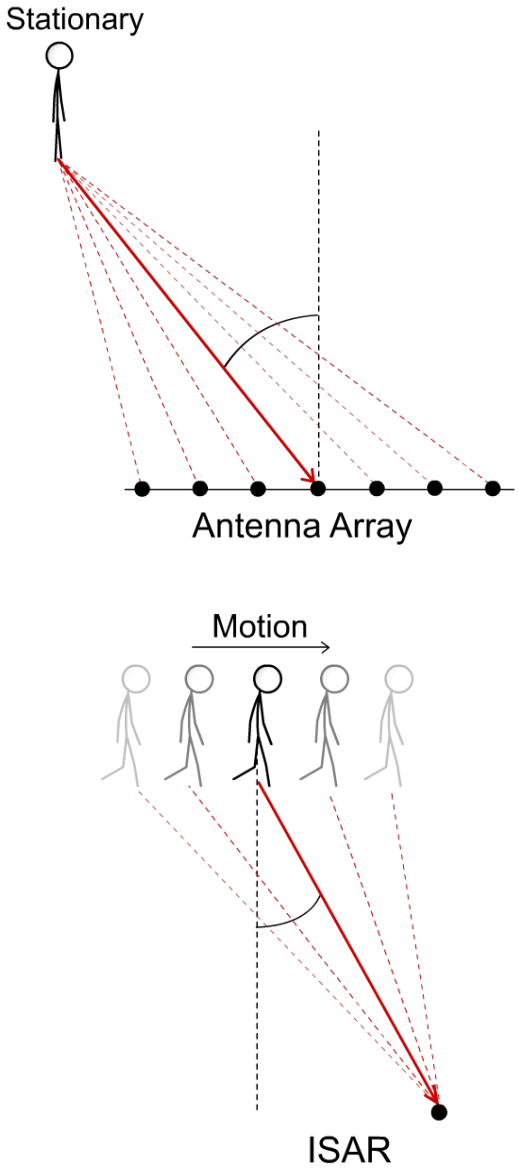
- Direct signal and reflections off the wall itself (multipath) are much stronger than reflections of interest
- Signals pass wall twice → much weaker

- MIMO interference nulling to remove reflections from static objects
  1. Estimate channels
  2. Use estimates to null signal at receiver
  3. Objects that moved between step 1 and 2 can be detected
  4. Repeat iteratively

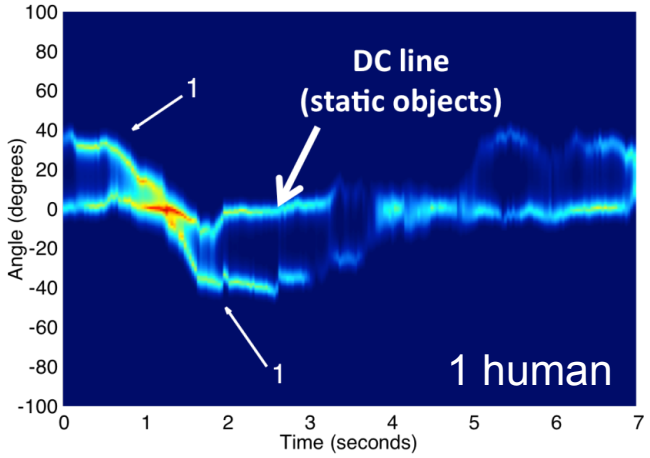


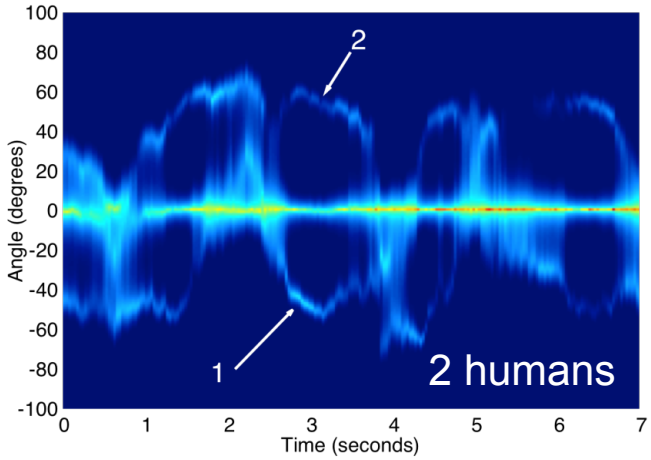
Tracking Humans

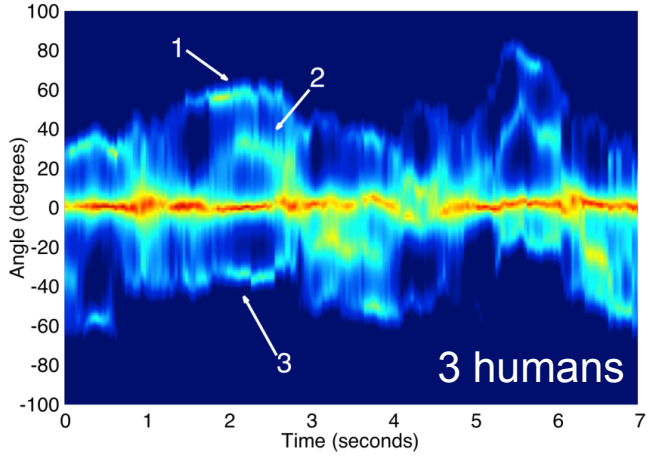
- Inverse synthetic aperture radar (ISAR) to simulate antenna array
  - Cheaper, since less antennas needed
  - More compact
  - Assumptions on speed of motion
- Estimate angle (relative movement)
- Smoothed MUSIC algorithm to separate multiple humans



Tracking Humans







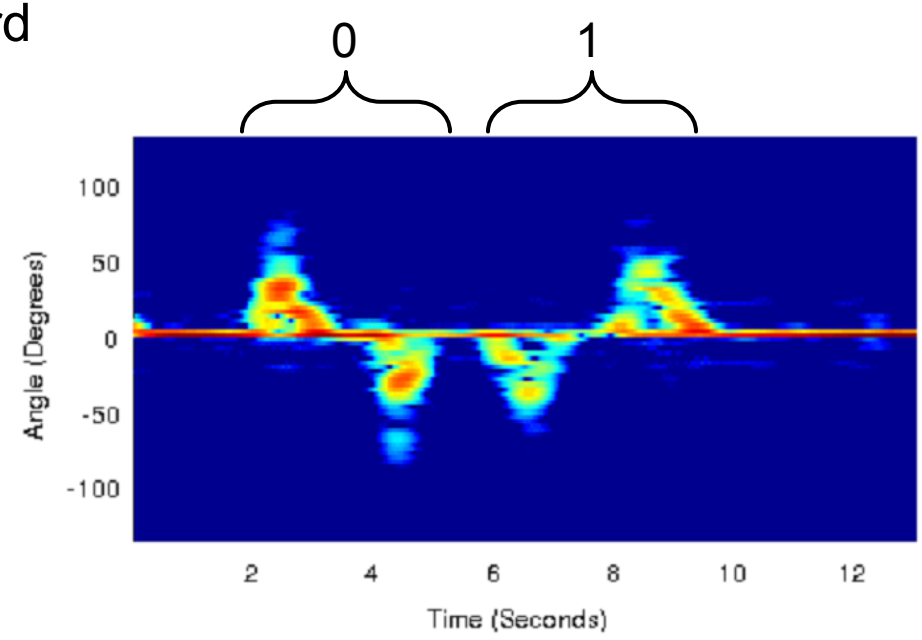
- Positive angle → moving towards device
- Negative angle → moving away from device
- Brightness (typically) indicates distance

- Spatial variance with trained thresholds to automatically obtain number of humans

[Adib2013]

Gesture Recognition

- Special mode to send messages
- Bits encoded by gestures
  - “0”: step forward, step backward
  - “1”: step backward, step forward
- Requires knowledge about coarse location of device



[Adib2013]

Experimental Setup

- Two standard conference rooms (7×4 and 11×7 meters)
- 15cm-wide hollow walls, supported by steel frames with sheetrock on top
- Wi-Vi placed one meter away from wall in neighboring room

- 8 human subjects of different heights and builds
  - Subsets of up to 3 people for experiments on detecting humans
  - One human at a time for experiments on gesture recognition

Evaluation: Detecting Number of Humans

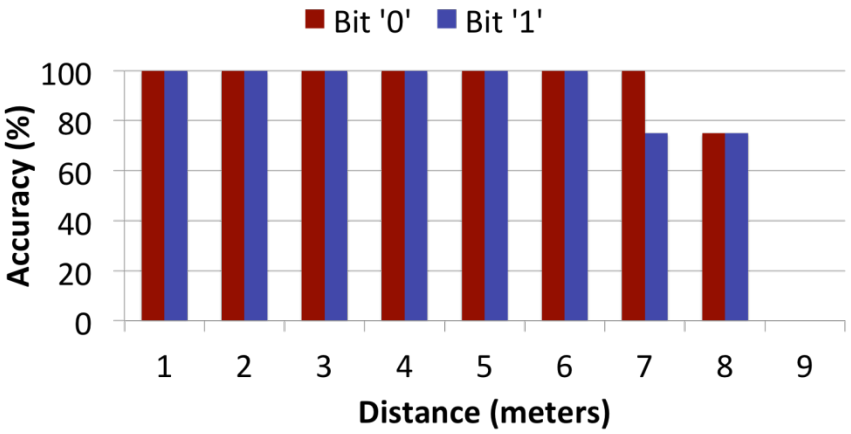
- One conference room for training, one for testing
- Test subjects entered room, closed door and moved freely

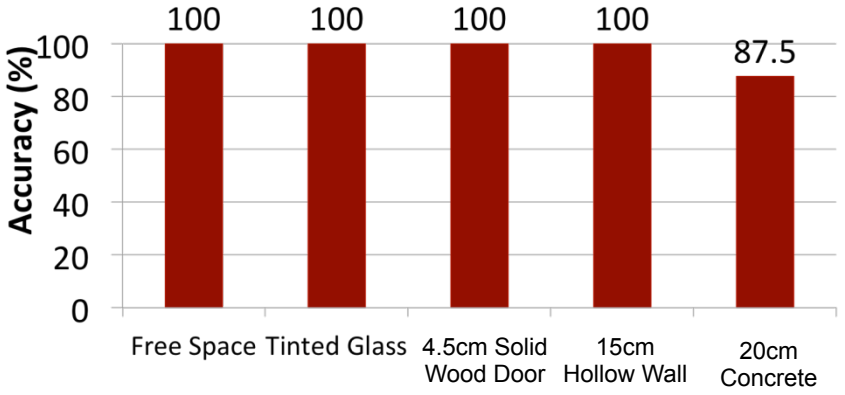
Detected

Actual	0	1	2	3
0	100%	0%	0%	0%
1	0%	100%	0%	0%
2	0%	0%	85%	15%
3	0%	0%	10%	90%

Evaluation: Decoding Gestures

- No mismatched bits, only erasure errors
- “0”-bits easier to detect than “1”-bits
  - Stepping forward, then backward is easier than the opposite
  - Subjects are closer to device on average when performing “0”-bits

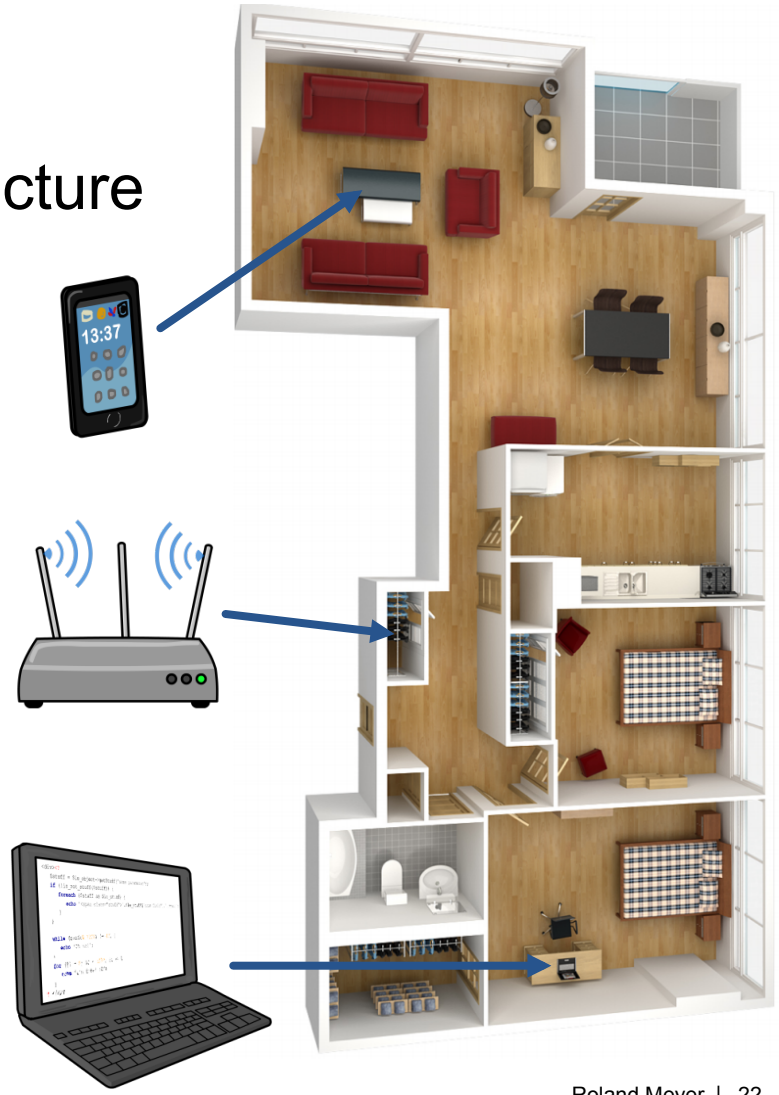




[Adib2013]

WiSee : „ Whole-Home Gesture Recognition Using Wireless Signals”

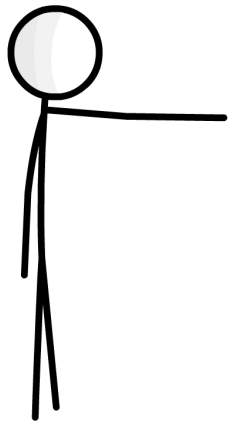
- Leverage existing Wi-Fi infrastructure
  - 1 AP as multi-antenna receiver
  - Few devices as transmitters
- Use Doppler shifts to measure movement speeds to identify gestures



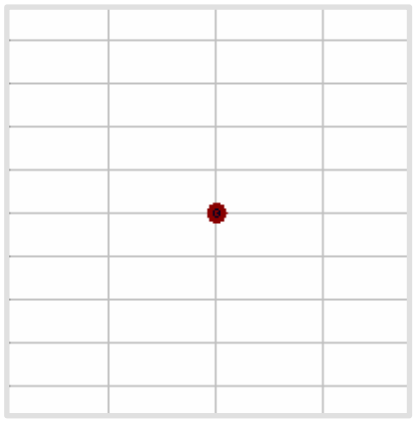
[Pu2013]

Applications for WiSee

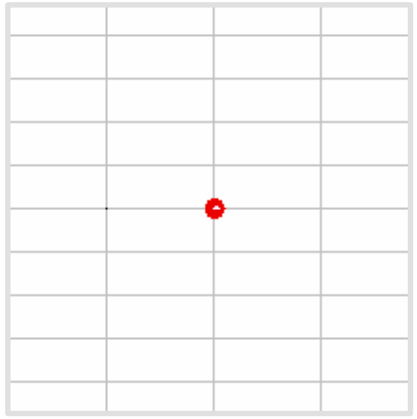
- Always-available control over household appliances
  - Adjust music volume
  - Adjust room temperature
  - Turn lights on/off
  - Change TV channels
  - Gaming
- Secret gestures for user identification



Doppler Shift



- Static object
  - Emitted waves have same frequency everywhere

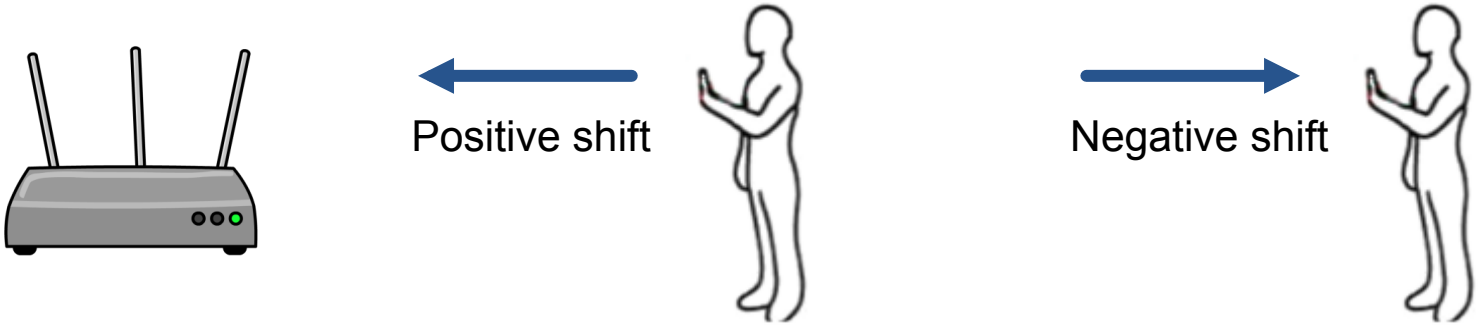


- Moving object
  - Frequency perceived higher when approaching
    → positive shift
  - Lower when retreating
    → negative shift

Image Source: Wikipedia

Extracting Doppler Shifts from Wireless Signals

- Humans reflecting Wi-Fi signals act as virtual transmitters

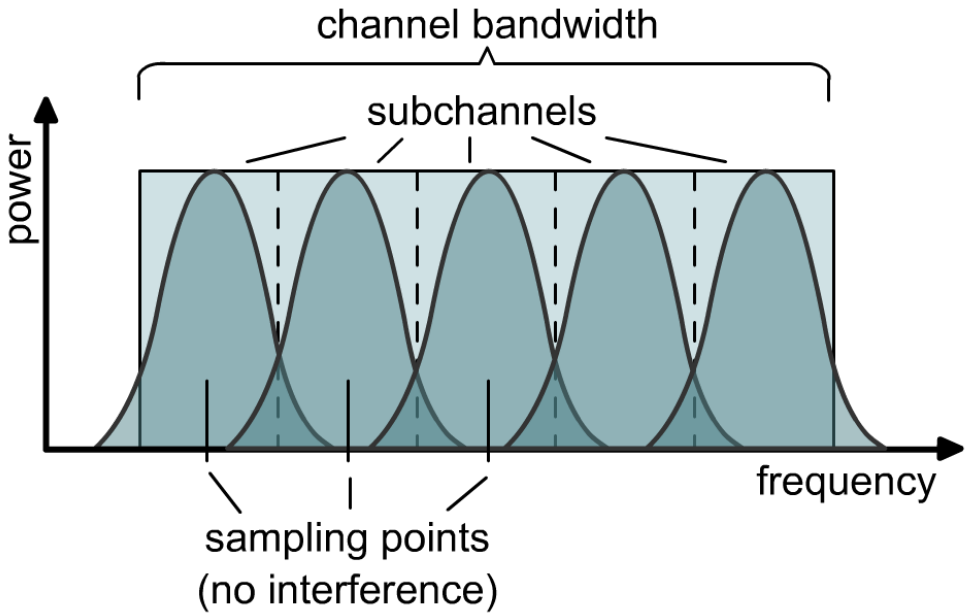


- Frequency shift depends on original frequency, speed and direction of movement
- Human motion results in very small shifts
  - A motion of 0.5 m/s within a 5 GHz transmission results in a maximum shift of 17 Hz → difficult to detect

[Pu2013]

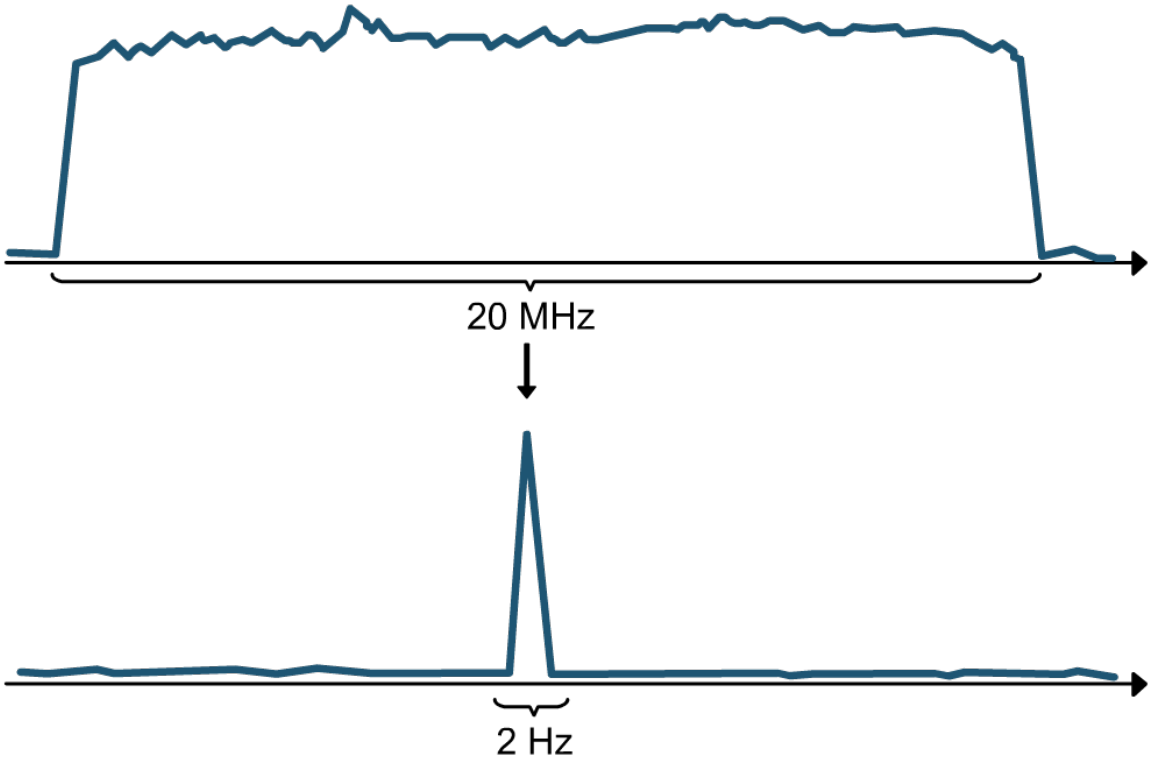
OFDM (Orthogonal Frequency Division Multiplexing)

- Increase throughput by multiplexing a single wide channel into multiple orthogonal (non-interfering) subchannels



- Widely used, e.g. in DVB-T, LTE, digital radio, …

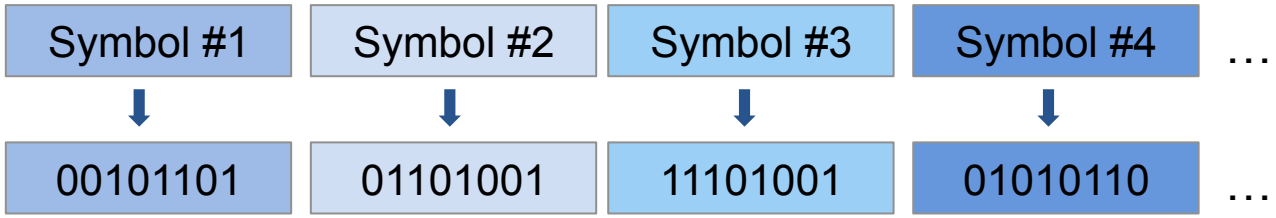
Extracting Doppler Shifts from Wireless Signals



- Challenge: Detect frequency shifts many magnitudes smaller than the bandwidth

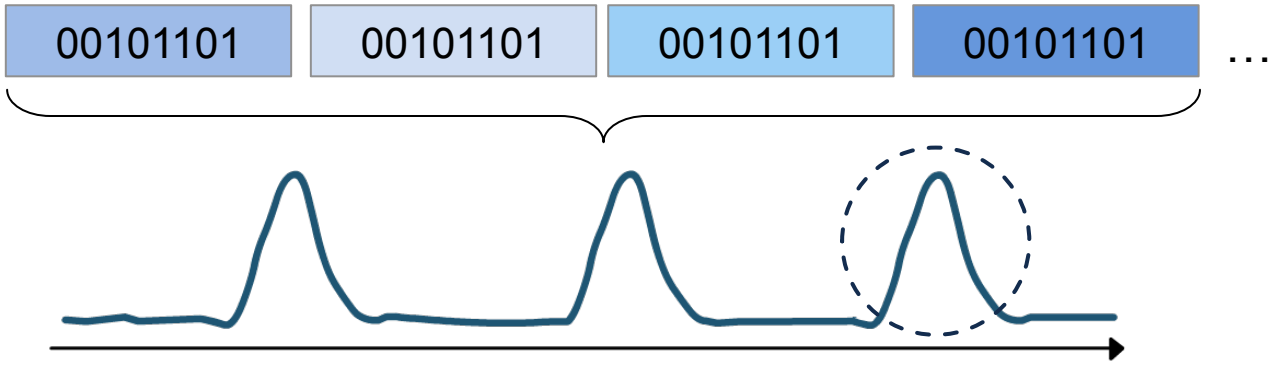
Extracting Doppler Shifts from Wireless Signals

1. Decode received OFDM symbols using standard decoder

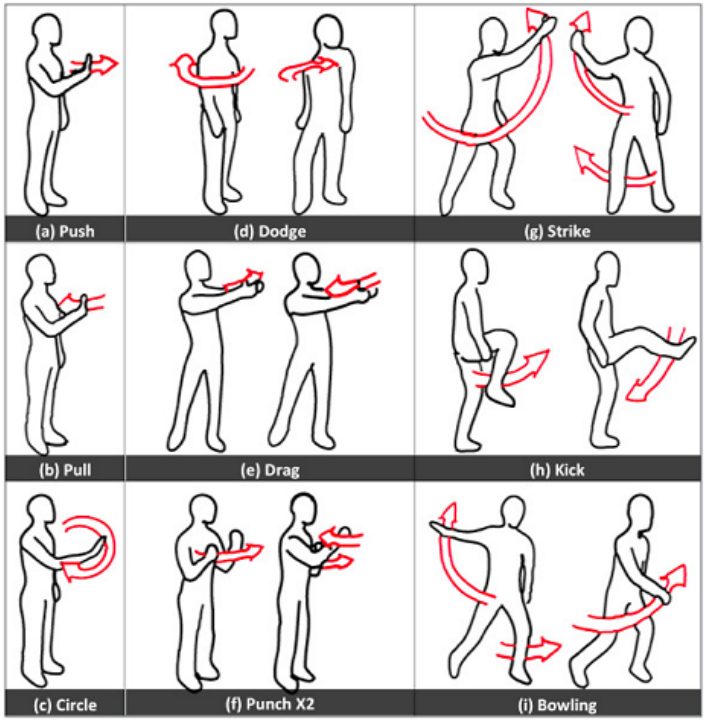


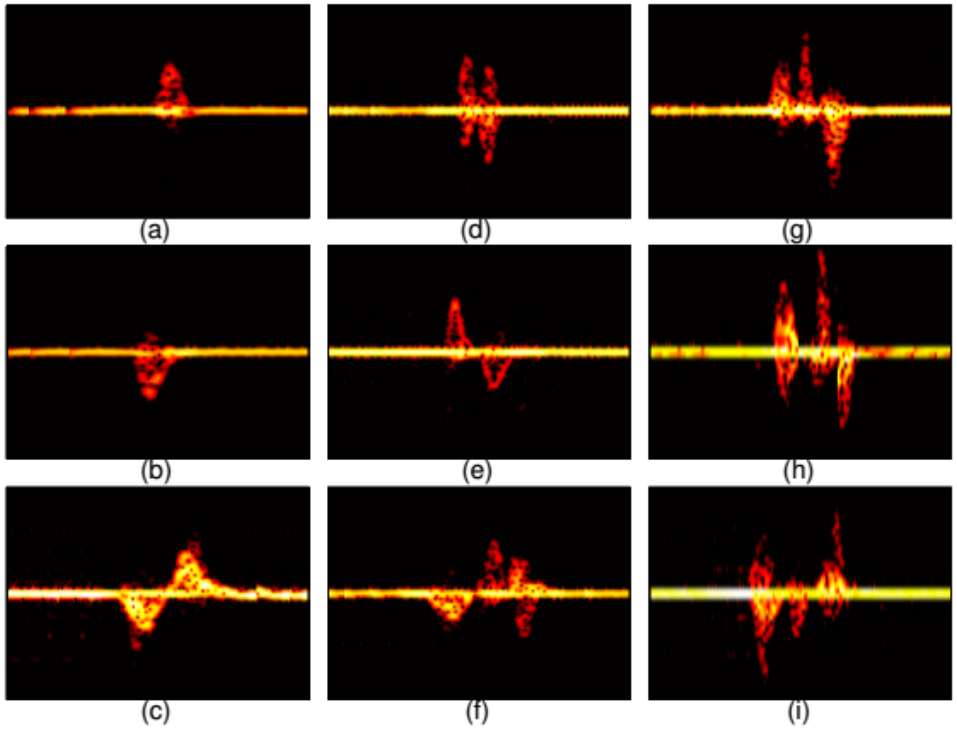
2. Use the decoded data to transform and re-encode all symbols into the first symbol, removing the data part and only leaving the “noise”

3. Perform FFT over N symbols to reduce bandwidth by factor of N



Gestures



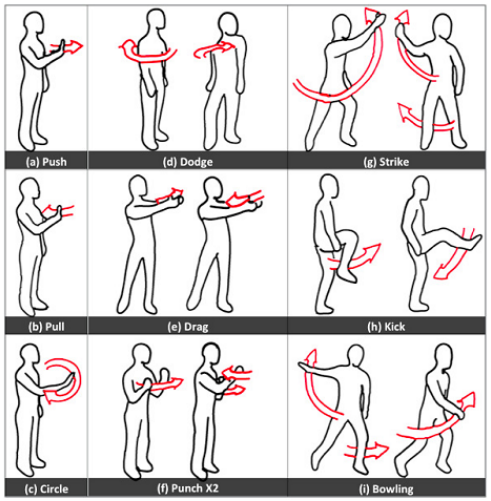


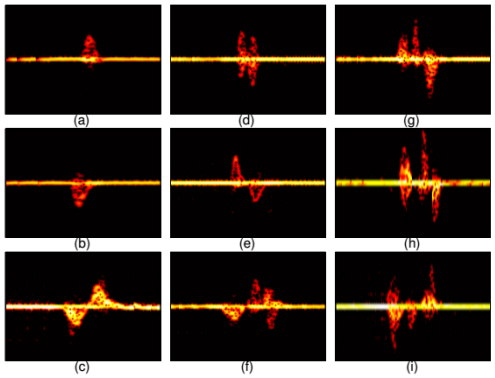
- Multiple body parts move at different speeds
  → multiple Doppler shifts

[Pu2013]

Gestures

- Use changes in energy to detect beginning and ending of gestures
- If separated by less than one second, cluster two gestures into one
- Pattern matching on number and order of positive and negative shifts
  - User independent
  - Speed independent

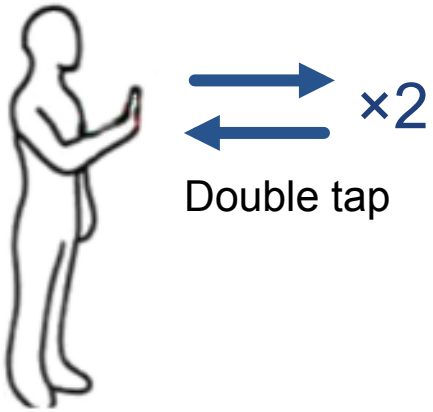




[Pu2013]

Dealing with Multiple Humans

- No standard MIMO channel estimation possible
  - No known preamble
- User performs preamble gesture to gain control



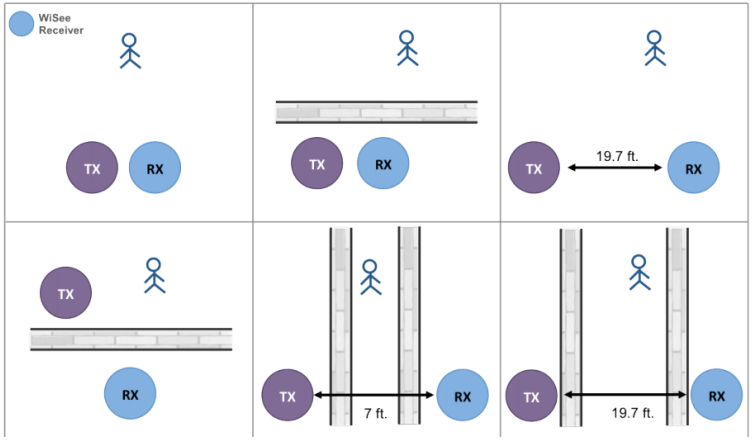
- Upon preamble detection iteratively use MIMO to estimate optimal channel and lock onto the user

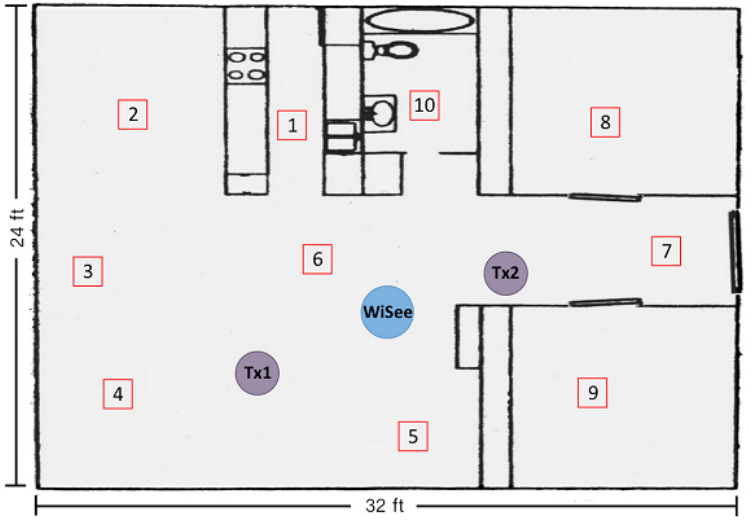
[Pu2013]

Experimental Setup

- Office building
  - 14.5cm-wide sheet-rock walls
  - Multiple other Wi-Fi devices operating in the area
- Two-bedroom apartment
  - 14cm-wide hollow walls
  - Wooden doors

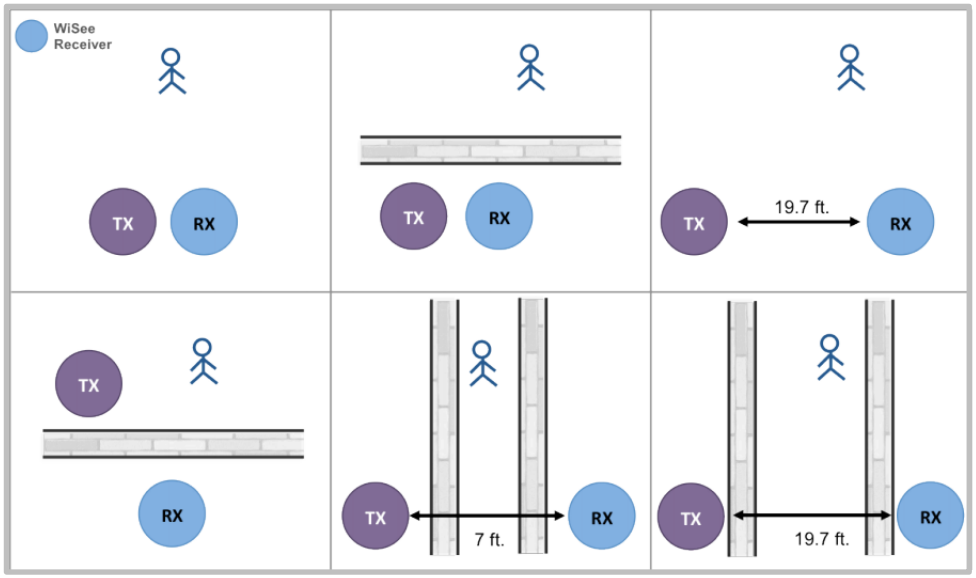
- 1 - 2 transmitting devices
- 5-antenna receiver
- 5 human subjects





[Pu2013]

Evaluation: Gesture Detection

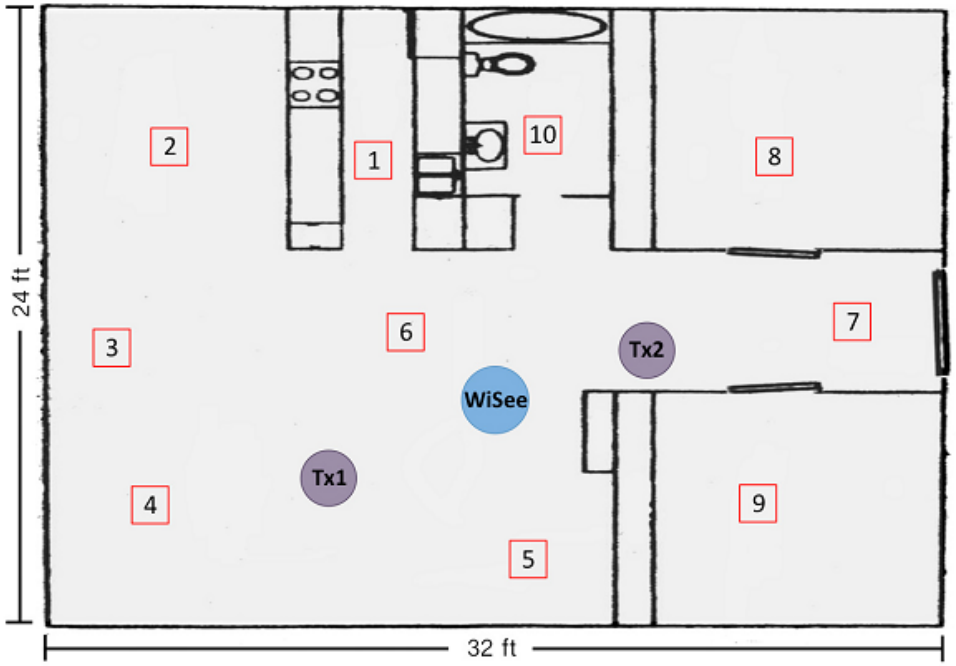


- 3 - 4 antennas is enough to detect gestures in all scenarios
- User has to be in range of receiver
  - Can be increased by increasing number of transmitters or distance between transmitters and receivers

[Pu2013]

Evaluation: Gesture Recognition

- 900 gestures performed
- 94% classified correctly
- 4% classified incorrectly
- 2% not detected

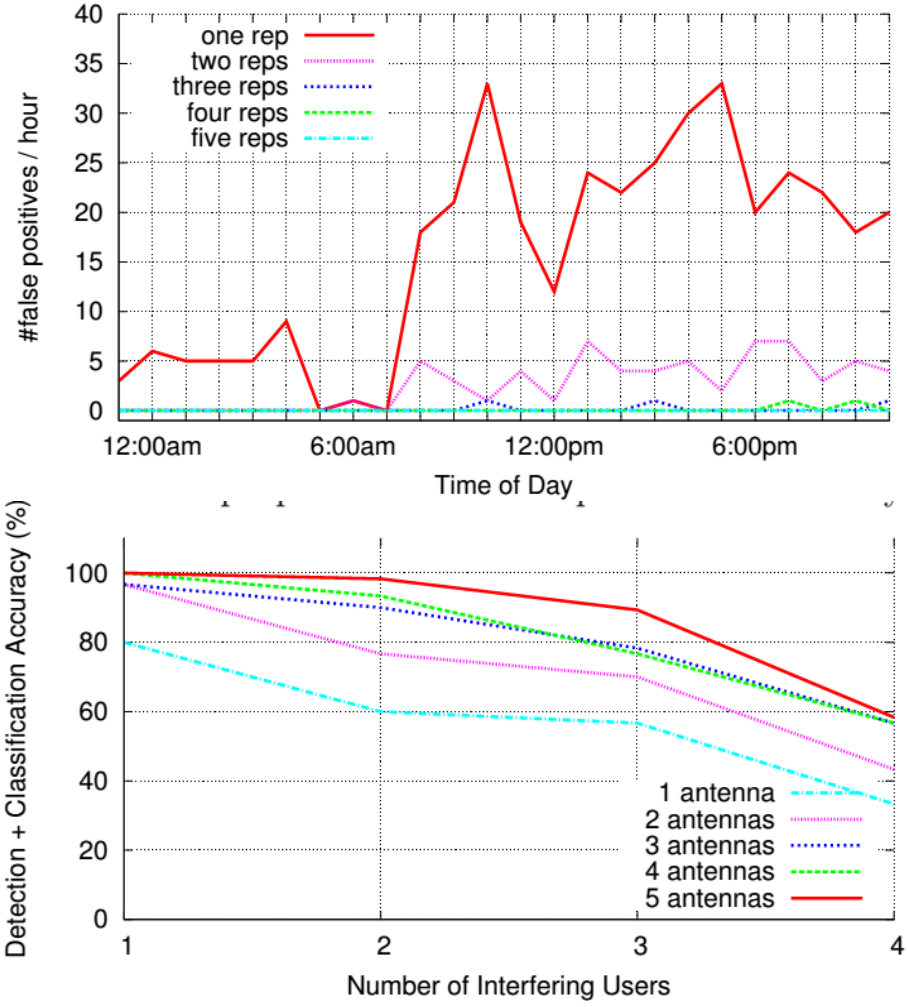


- Accuracy of distinguishing between gestures is high even when transmitters are active only 3% of the time

[Pu2013]

Evaluation: Handling Multiple Humans

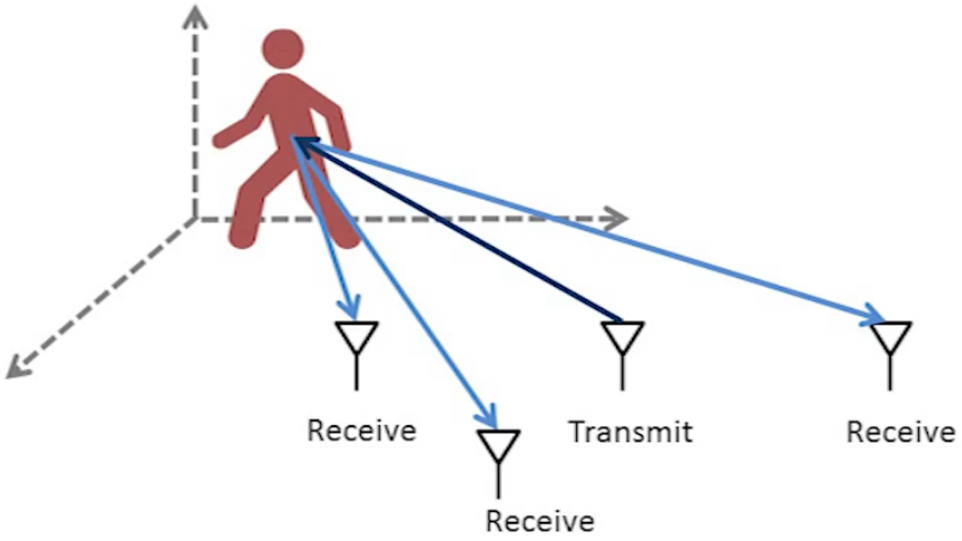
- False detection rate decreases with number of preamble repetitions
  - < 0.13 per hour with 3 repetitions
  - None with 4 repetitions
- 90% accuracy with 5 receiving antennas and 3 interfering users



WiTrack : “3D Tracking via Body Radio Reflections”

- 3D tracking of humans
- Coarse detection of moving body parts
- Measure time-of-flight of reflections to estimate location

- Localizes the center of a human body to within 10 to 13 cm horizontally and 21 cm vertically



[Adib2014]

Applications for WiTrack

- Augment virtual-reality and gaming systems to work in non-line-of-sight scenarios
- Elderly fall detection
  - Possible because height and speed of movement is tracked
- Control appliances by pointing at them
  - Possible because orientation of body parts is tracked

AllSee: “Bringing Gesture Recognition To All Devices”

- Extract gesture information from ambient background signals (e.g. TV broadcasting)
- Signal amplitude is extracted using only analog hardware components
  - No need for power-hungry components
- Leverage the fact that motion closer to the receiver causes more signal attenuation
- Negligible power consumption
  - Can be used in batteryless devices

[Bryce2014]

Summary

- Wireless signals traditionally used for communication, but many more applications possible
  - Localization & motion tracking
  - Gesture recognition
  - Through-wall imaging and communication
- Potential for the Internet of Things
  - (Re)use existing wireless infrastructure
  - No (body) instrumentation needed
  - No requirement for line-of-sight
  - Cover large areas with few devices
  - Low power

Application Demos

- WiSee
- AllSee

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Thanks for Listening

- [Adib2013]
  Fadel Adib, Dina Katabi
  See Through Walls with Wi-Fi!
  Proceedings of the ACM SIGCOMM 2013, Hong Kong, China, 2013.
- [Pu2013]
  Qifan Pu, Sidhant Gupta, Shyamnath Gollakota, Shwetak Patel
  Whole-Home Gesture Recognition Using Wireless Signals
  Proceedings of the 19th annual international conference on Mobile computing & networking Mobicom'13, Miami, USA, 2013
- [Adib2014]
  Fadel Adib, Zachary Kabelac, Dina Katabi, Robert C. Miller.
  3D Tracking via Body Radio Reflections
  Usenix NSDI'14, Seattle, USA, 2014
- [Liu2013]
  Vincent Liu, Aaron Parks, Vamsi Tall, Shyamnath Gollakota, David Weatherall, Joshua Smith
  Ambient Backscatter: Wireless Communication out of Thin Air
  Proceedings of the ACM SIGCOMM 2013, Hong Kong, China, 2013.
- [Bryce2014]
  Bryce Kellogg, Vamsi Tallat, Shyamnath Gollakota
  Bringing Gesture Recognition To All Devices
  Proceedings of the USENIX NSDI 2014, Seattle, USA, 2014.