Wireless Communication Systems
@CS.NCTU

Lecture 7: MobileHCI

Instructor: Kate Ching-Ju Lin (林靖茹)

Traditionally, wireless signals are used for …

Data communication among devices

Now, we have internet of ***Things***

More and more sensing/wearable devices, wireless signals everywhere

Can we use wireless signals to create

human-centric applications,

not just for data communication?

Why Device-Free?

Limitation of Cameras

- Privacy issues
- Line of sight limitation
- Lighting requirement

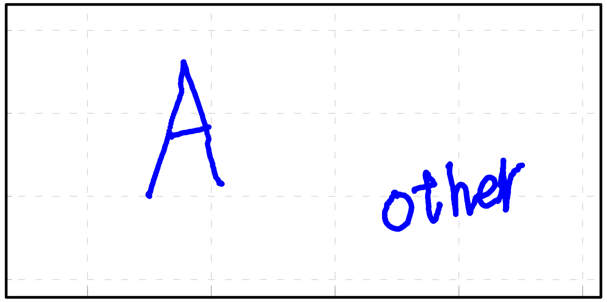
Limitation of Wearable Devices

- Inconvenient
- High deployment cost
- Feedback overhead

Device-Free MobileHCI Apps

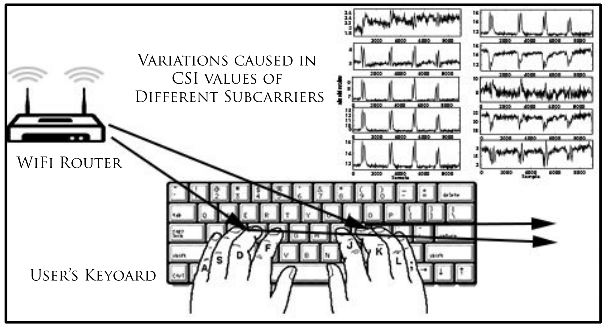
[MobiCom'13]

Gesture recognition



[MobiCom'15]

Handwriting



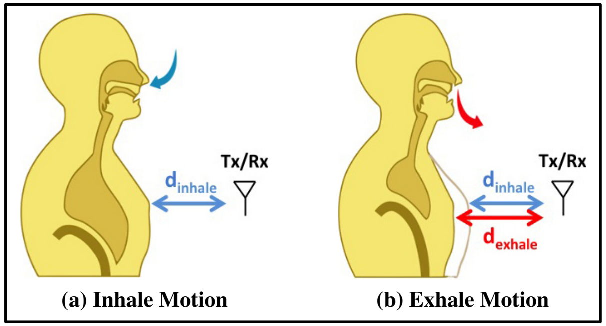
[Mobicom'15]

Keystroke

Device-Free HealthCare Apps

[NSDI'14]

Fall detection



[CHI'15, MobiCom'16]

Breathing and heart-rate monitoring

Emotion detection

[MobiSys'15]

Sleep Apnea Diagnosis

WiSee

Device-free gesture recognition

using wireless signals [MobiCom'13]

Qifan Pu, Sidhant Gupta, Shyam Gollakota, Shwetak Patel

University of Washington

Idea: Doppler shift

- Frequency change of a wave occurs as its source moves relative to the observer

source: https://en.wikipedia.org/wiki/Doppler_effect

Velocity of the signal receiver (observer)

$$f' = \left(\frac{c + v_r}{c}\right) f \Rightarrow \Delta f = f' - f = \frac{f}{c} v_r$$

Speed of light

$v_r \uparrow$ $\Delta f \uparrow$

Doppler Effect Caused by Human Mobility

- When a user is mobile, Rx will observe the Doppler effect even if Rx itself is static
  - **Why?** The length of the reflected path varies over time
- If the moving speed is v, what's the Doppler effect
  - $\Delta f \leq (2f/c) * v$ → **Why?**

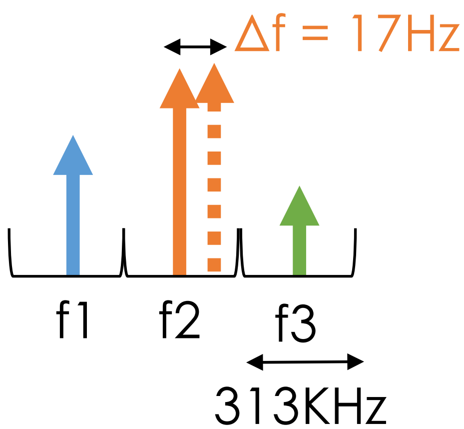
Velocity of Rx along the reflected path is at most 2v

Detect the gesture by measuring the Doppler effect at Rx → **Device-free**!

Is it that Simple?

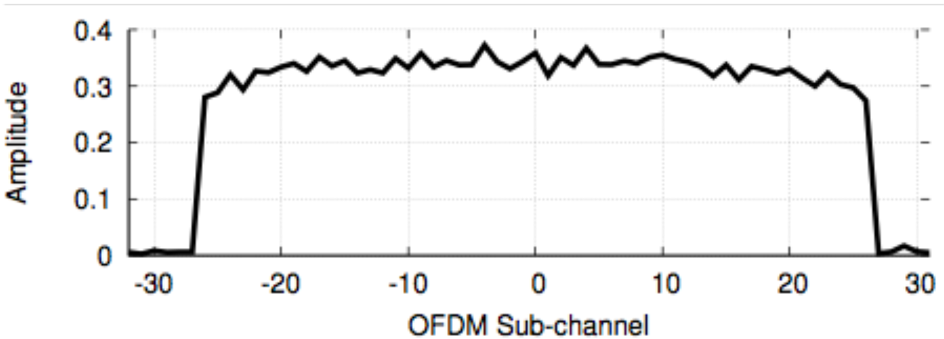
- Challenge 1
  - The velocity of a human gesture is VERY SMALL (e.g., 0.5 m/s)
  - Correspond to a small Doppler shift
    e.g., $\Delta f = 2fv/C$ = **17Hz** when v = 0.5 m/s and f = 5GHz
- Challenge 2
  - WiFi operates in the 20MHz wide band
    → Corse resolution!!
  - Each 802.111 OFDM symbol includes 64 subcarriers
    → bandwidth of each subcarrier
    = $20*10^6/64$ ~ 313KHz

Cannot observe 17Hz within a 312.5KHz band

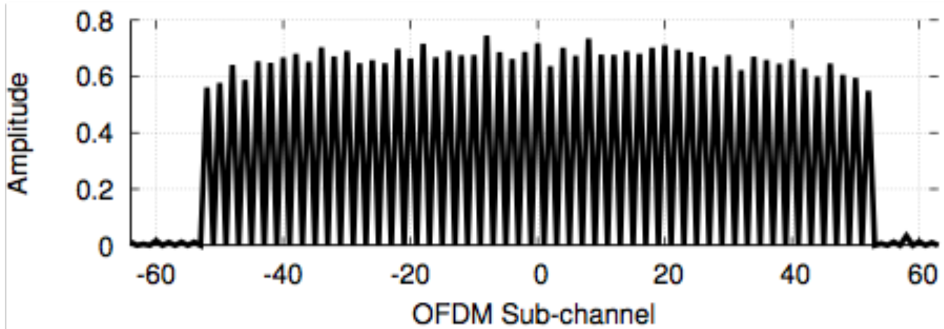


How to Identify Small Shift
even in Wideband Channels?

Idea: Transform the WiFi signals to narrowband pulses via large FFT!



FFT over one symbol



FFT over two identical symbol

Large FFT

IFFT
$$x_k = \sum_{n=1}^{N} X_n e^{i2\pi kn/N}$$

FFT
$$X_n = \sum_{k=1}^{N} x_k e^{-i2\pi kn/N}$$

- Assume Tx sends two identical symbols, each with N sample
- If Rx performs a 2N point FFT

$$X_n = \sum_{k=1}^{N} x_k e^{-i2\pi kn/2N} + \sum_{k=N+1}^{2N} x_k e^{-i2\pi kn/2N}$$
$$= \sum_{k=1}^{N} x_k e^{-i2\pi kn/2N} + \sum_{k=1}^{N} x_k e^{-i2\pi (k+N)n/2N}$$
$$= \sum_{k=1}^{N} x_k e^{-i2\pi kn/2N} (1 + e^{-i\pi n})$$

Even sub-ch
$$X_{2l} = 2\sum_{k=1}^{N} x_k e^{-2\pi kl/N}$$
$$X_{2l+1} = 0$$
Odd sub-ch

1. Bandwidth of each subcarrier is halved!
2. In theory, odd subcarriers must be 0. Then, if Rx receives pulse in odd subcarriers → **Doppler effect**!!

How Large is FFT Required?

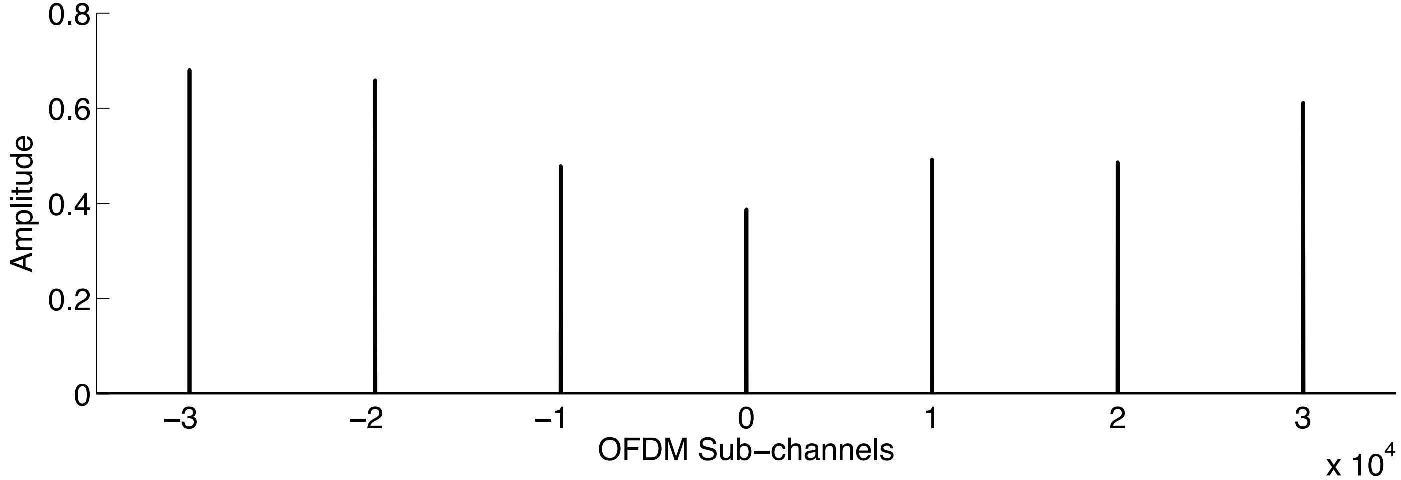
- 2N points FFT → halve the bandwidth
  - Each subcarrier is (20/64) /2 = 10(MHz)

- MN points FFT → reduce the bandwidth by M times
  - Each subcarrier is 20/M (MHz)

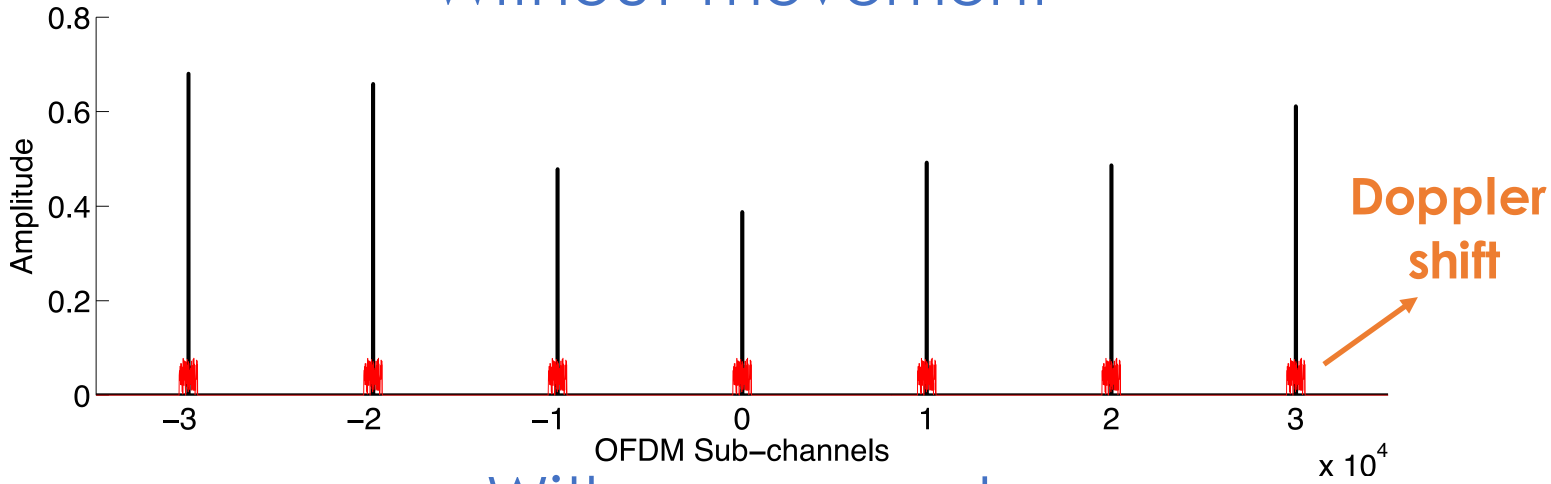
To get a resolution of 10Hz, we need $(20/64)*10^6/M = 10$
→ M = 31,250

Capturing Movement via Large FFT

FFT over 31,250 symbols → 10Hz per subcarrier

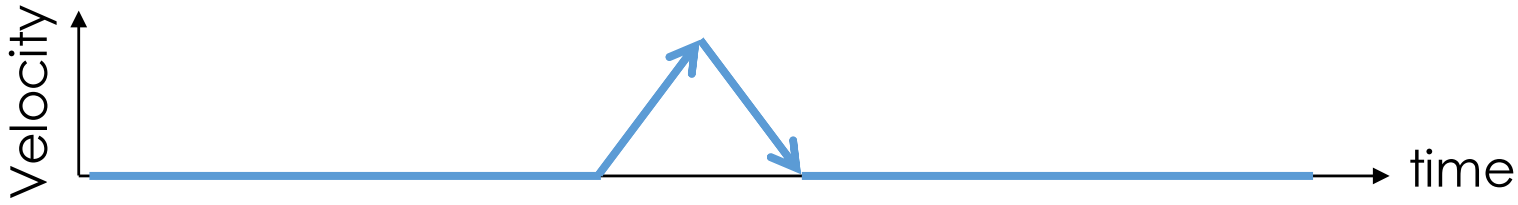


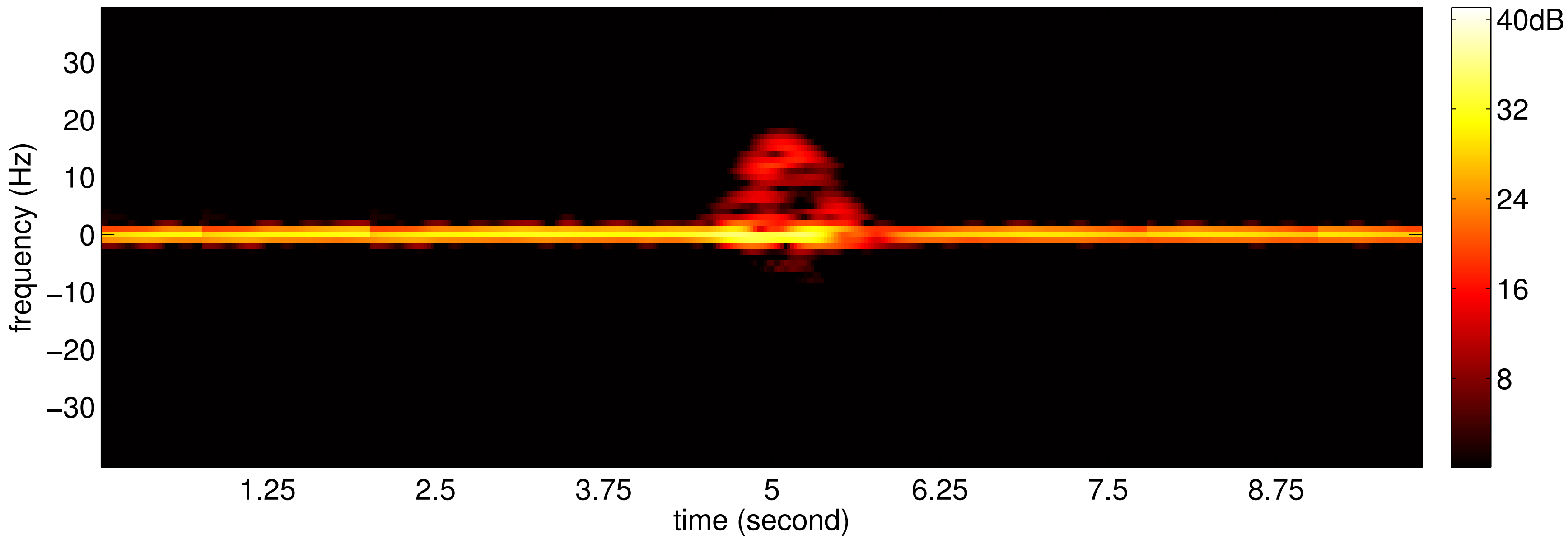
Without movement



With movement

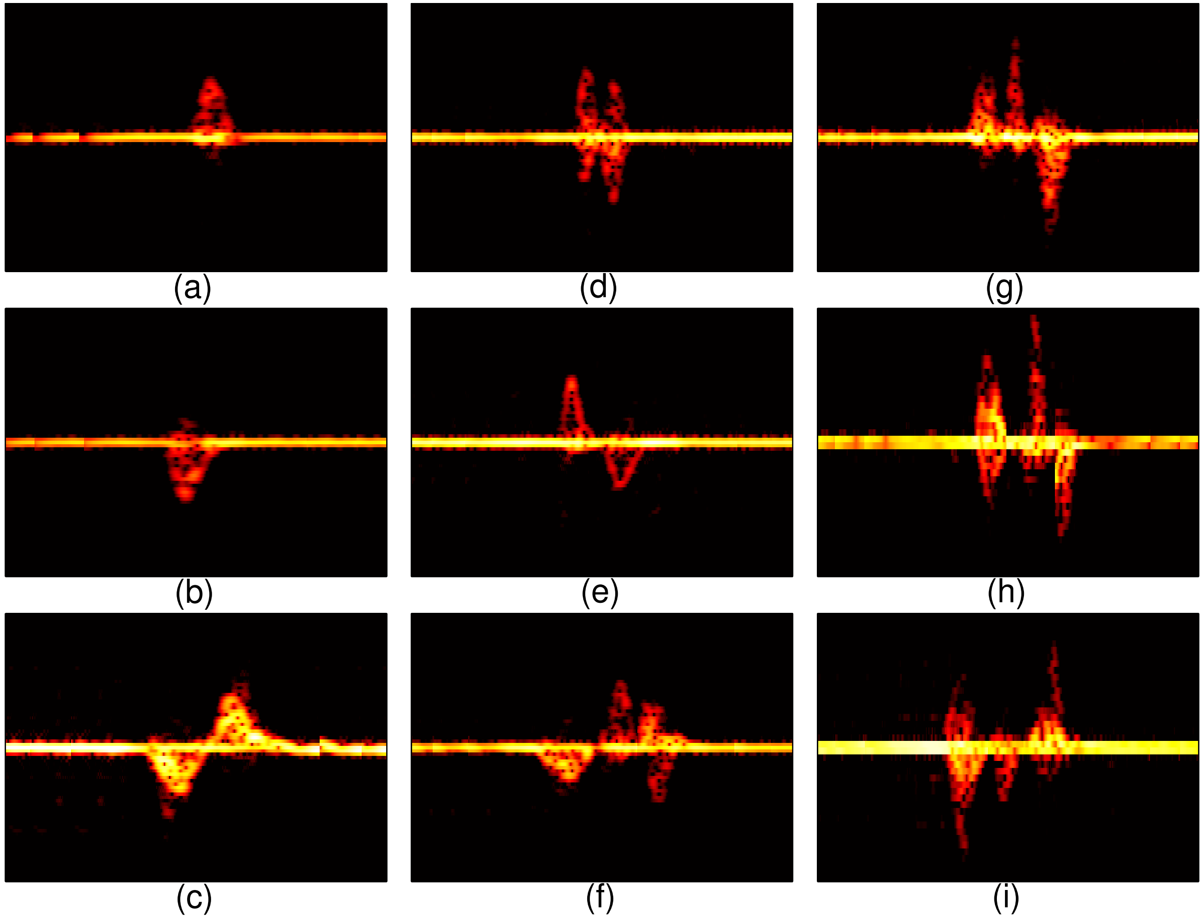
Capturing over Time





Frequency-time Doppler profile
of an example gesture (push)

Detection by Classification



Different gestures correspond to various frequency-time Doppler profiles

Classification

- Partition signals into segments
- Represent the moving pattern as a sequence of positive/negative Doppler Effects

Doppler Effect	Value
Positive	1
Negative	-1
Both Positive/Negative	2

Compare the received sequence with the set of pre-defined sequenced

Practical Issue

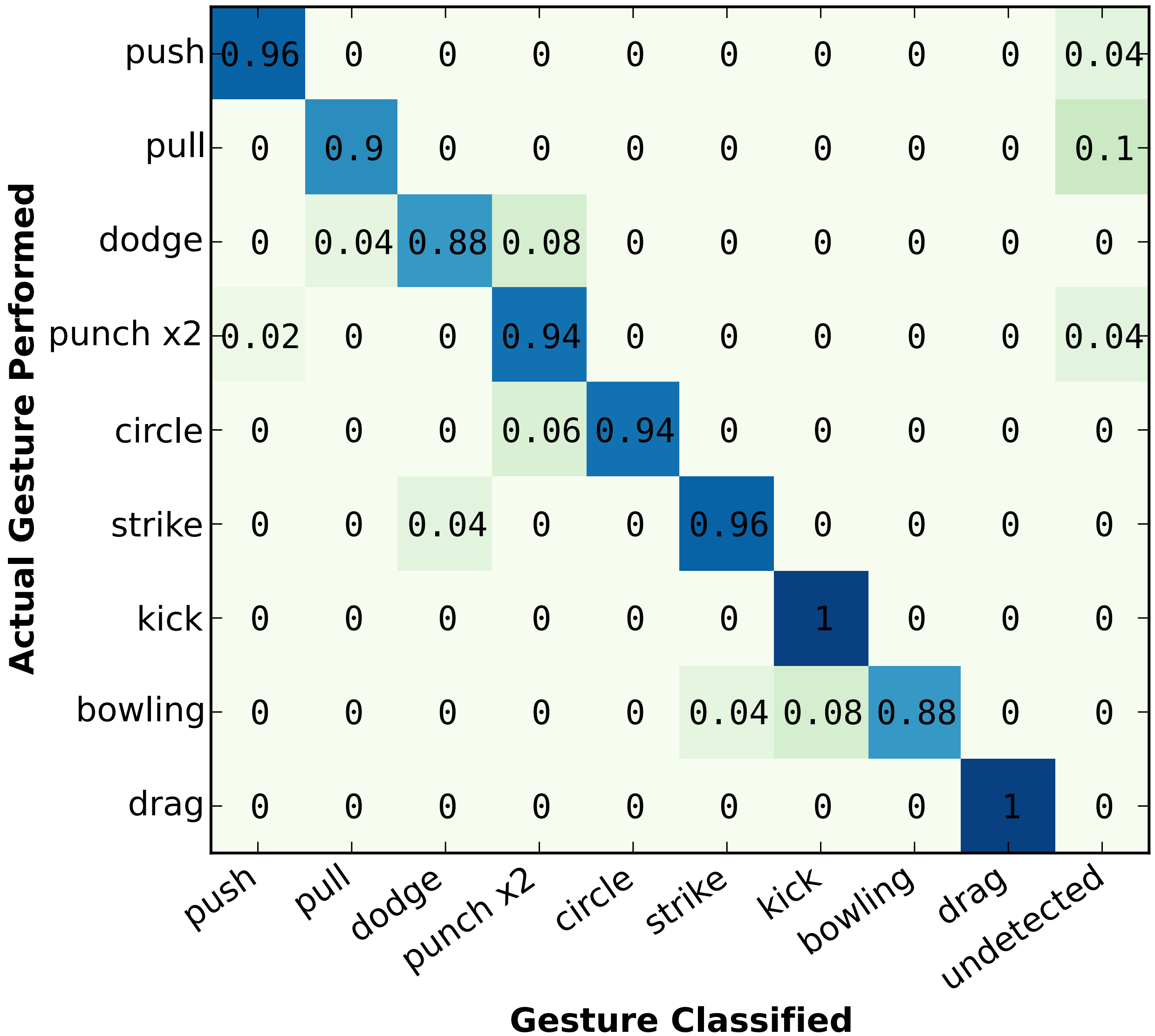
- Tx never sends the identical symbols over time
- Solution: Decode and re-encode
  - Decode the data symbol as usual
  - Re-encode the frequency-domain symbols

$$Y_1 = H_1X_1$$
$$Y_2 = H_2X_2 \rightarrow Y_2' = Y_2 * (X_1/X_2) \sim= H_2X_1$$
$$\vdots$$
$$Y_M = H_MX_M \rightarrow Y_M' = Y_M * (X_1/X_M) \sim= H_MX_1$$

  - Convert it back to time-domain $y'(m) = IFFT(Y'_m)$
  - Perform large FFT for $y'(0) \sim y'(M)$

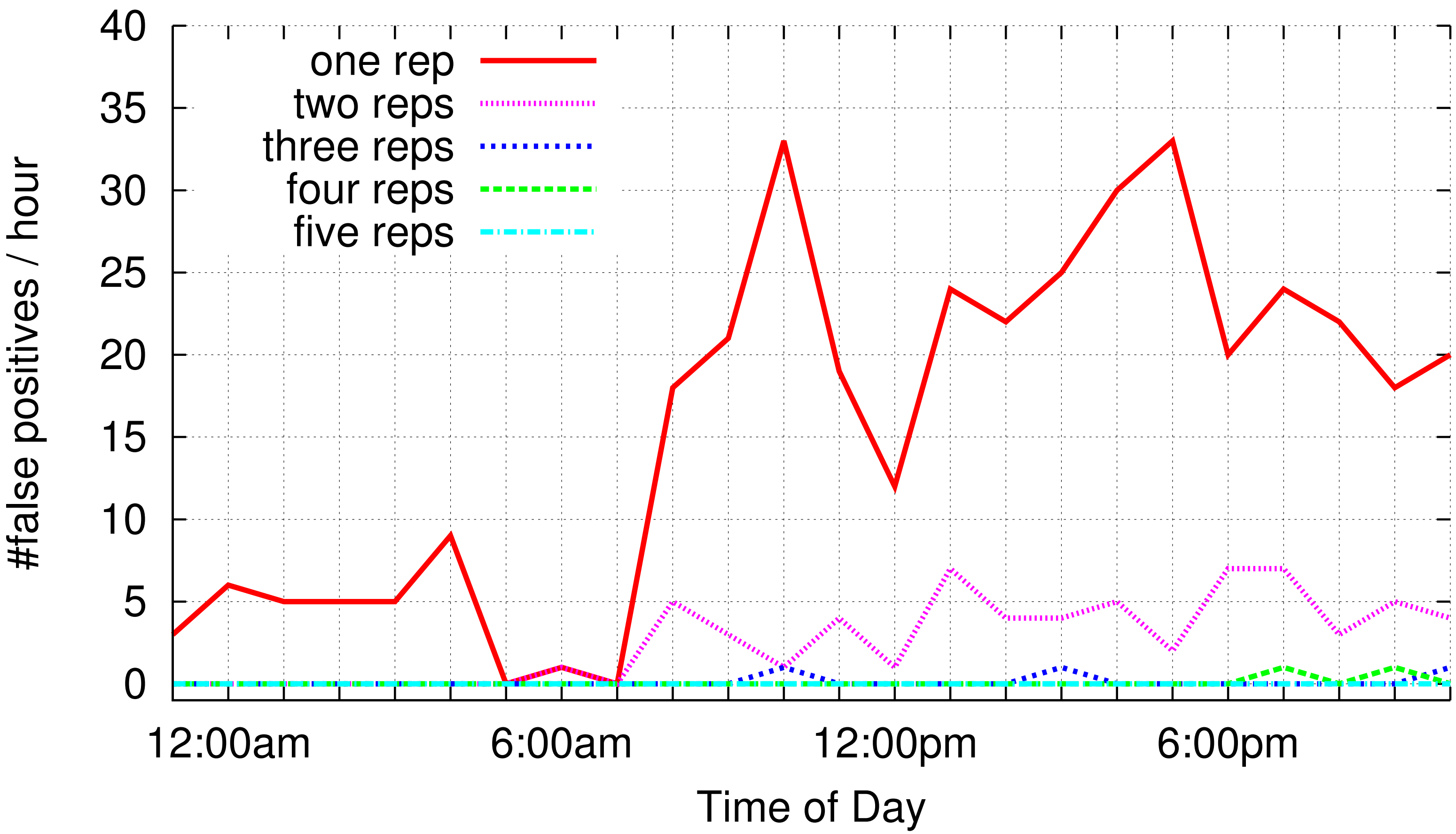
Performance – Accuracy

- Confusion matrix



Accuracy: .88~1

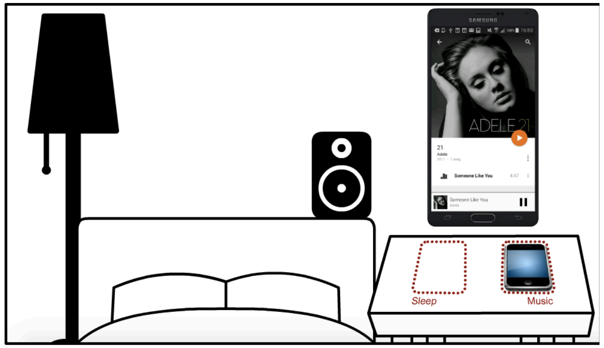
Performance – False Detection



False detection can be almost eliminated if the subject repeats the preamble (pre-defined gesture) several times

Concluding Remark

- First device-free wireless-based gesture recognition
- Leverage the Doppler Effect to detect gestures
- Improve the resolution using large FFT
- How to detect multiple persons?
  - Use multiple antennas
- Limitation: a finite set of detectable gesture
  - The Doppler shift patterns of different gestures should be distensible



EchoTag

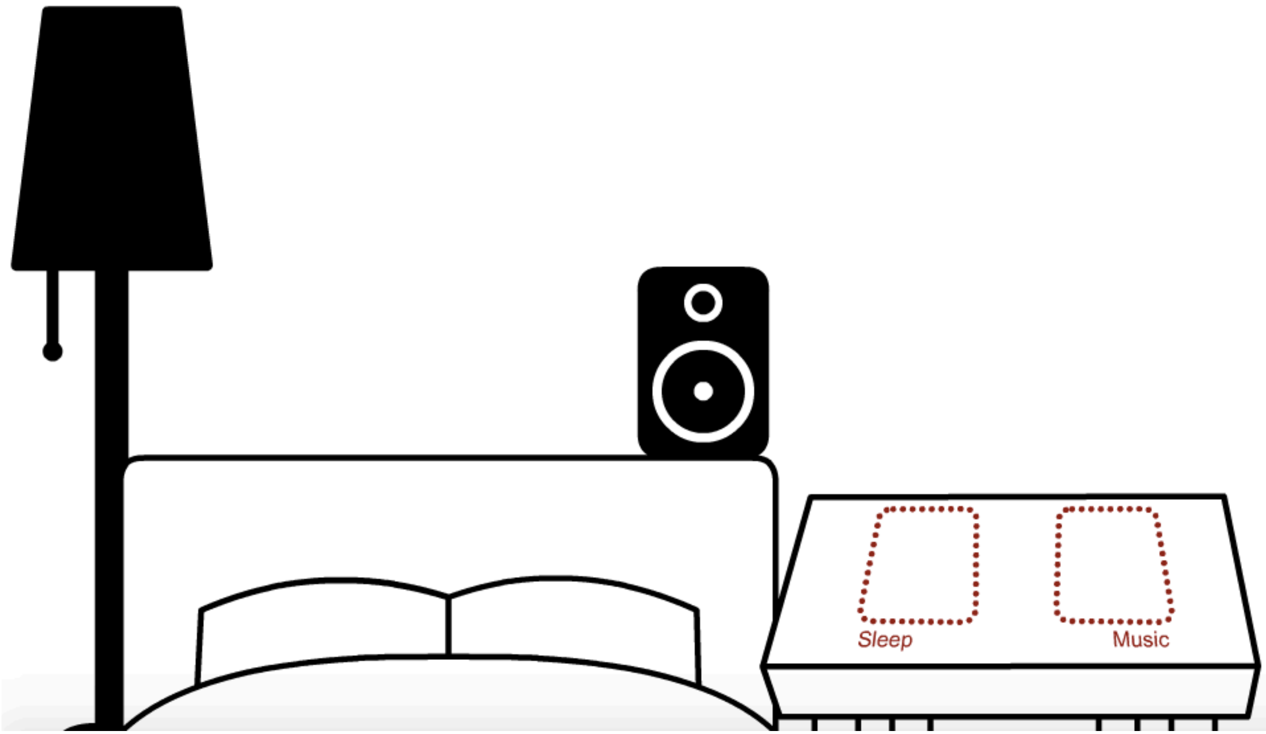
Infrastructure-free indoor localization tagging

[MobiCom'15]

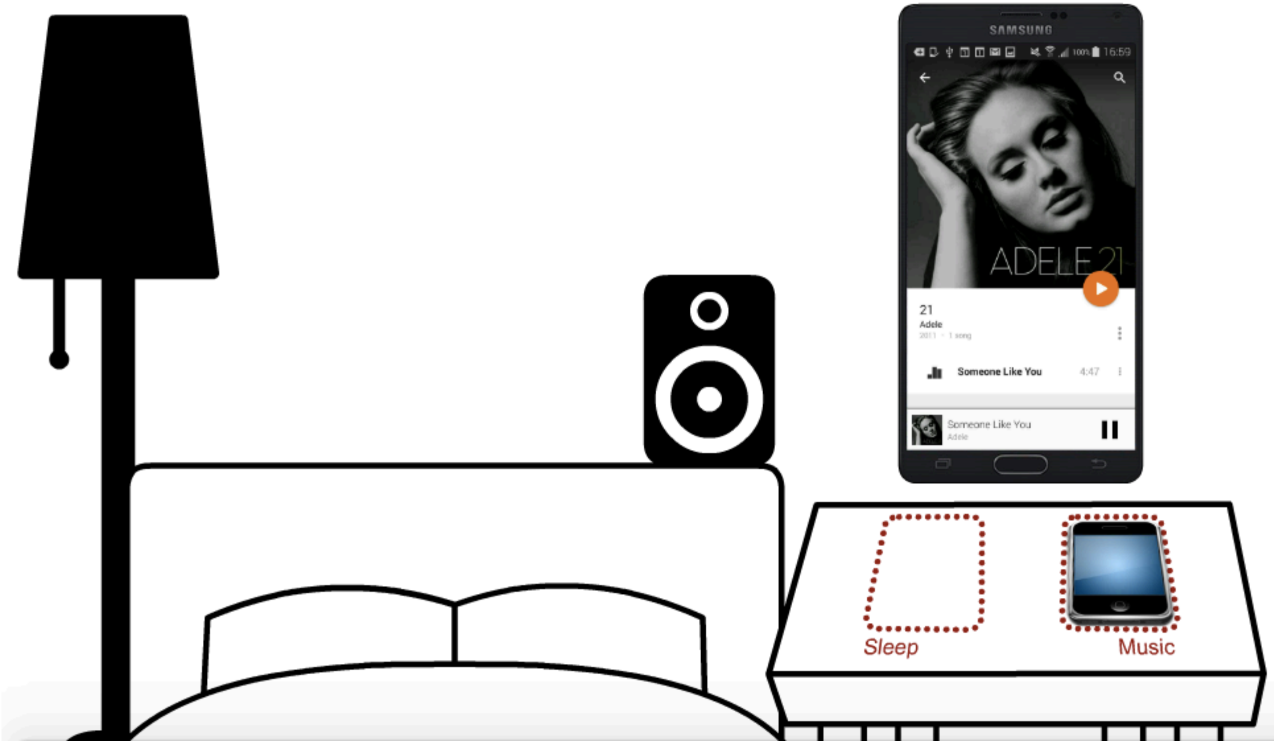
Yu-Chih Tung and Kang Shin

University of Michigan, Ann Arbor

What is Location Tagging?



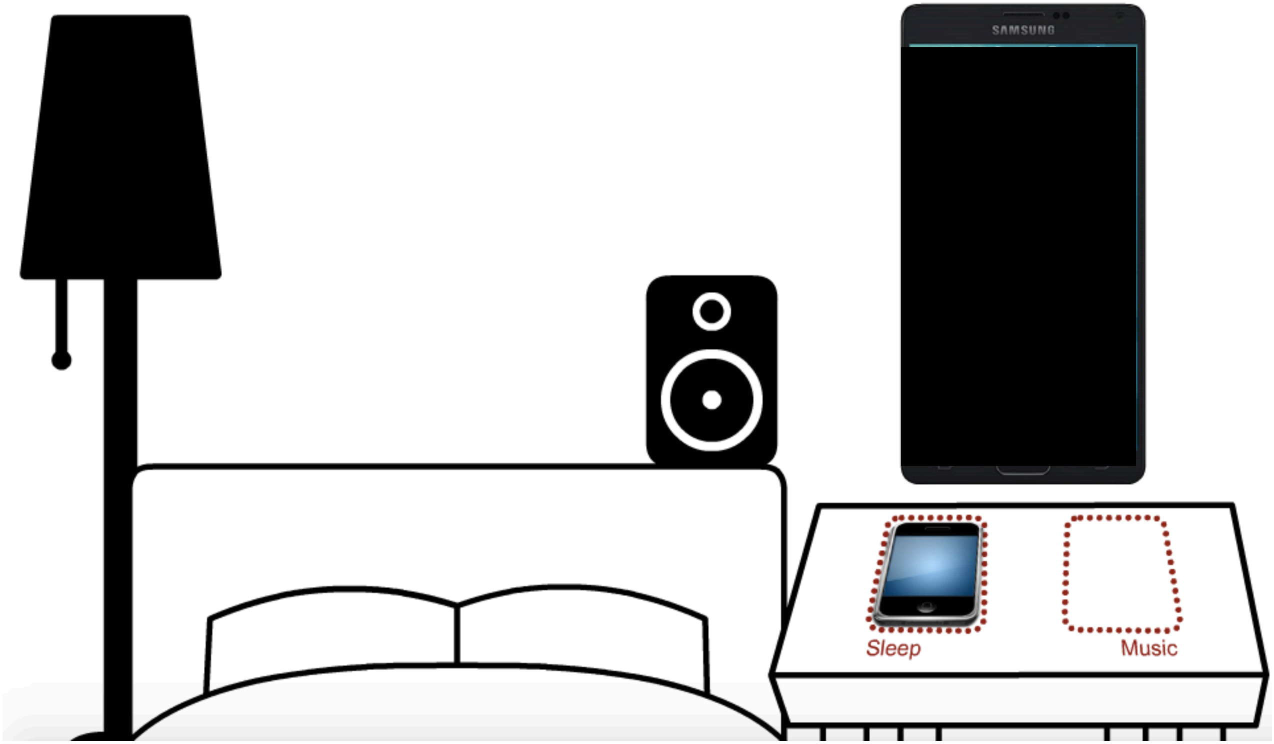
What is Location Tagging?



What is Location Tagging?

HOW?

Locate the position using **Acoustic Signals**!



Existing Solutions

• Infrastructure free

• Infrastructure-based

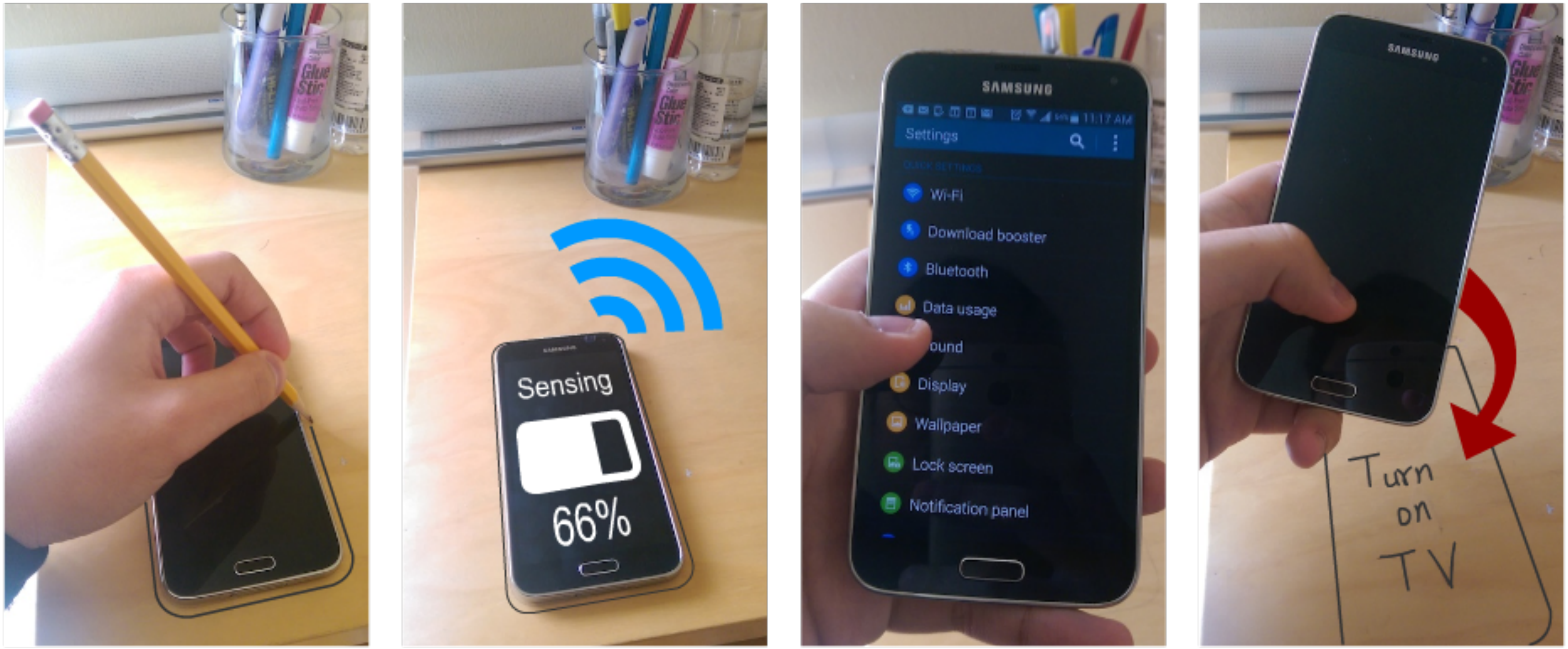
Existing Solutions

• Infrastructure free	Not accurate
– SurroundSense [Mobisys'09]	room-level
– Batphone [Mobisys'11]	room-level
– RoomSense [AH'11]	300cm
– Horse [Mobisys'05]	200cm
– Geo [Mobisys'11]	100cm
– FM [Mobisys'12]	30cm
• Infrastructure-based	Hard to deploy
– Luxapose [Mobisys'14]	10cm
– Cricket [Mobicom'00]	10cm
– Guoguo [Mobisys'13]	6-25cm

EchoTag

- Active acoustic sensing
- Fine sensing resolution based on built-in sensors (microphone and speaker)
- Low cost and easy deployment

How to Use EchoTag?



(a) Outline contour (b) Sense w/ sound (c) Select app (d) Replay tag

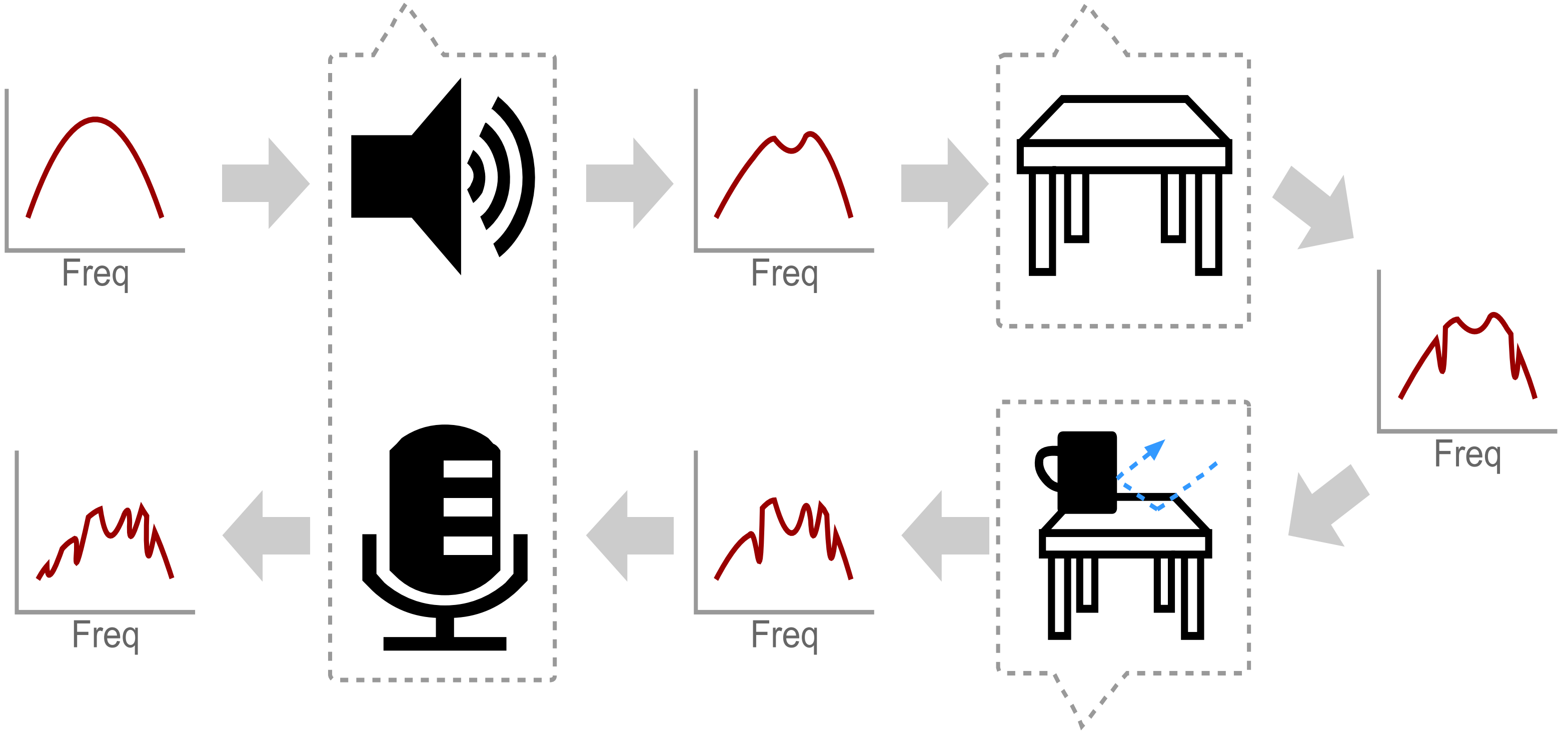
EchoTag

1. Active acoustic sensing
2. Classification and optimization

Sound Fingerprint

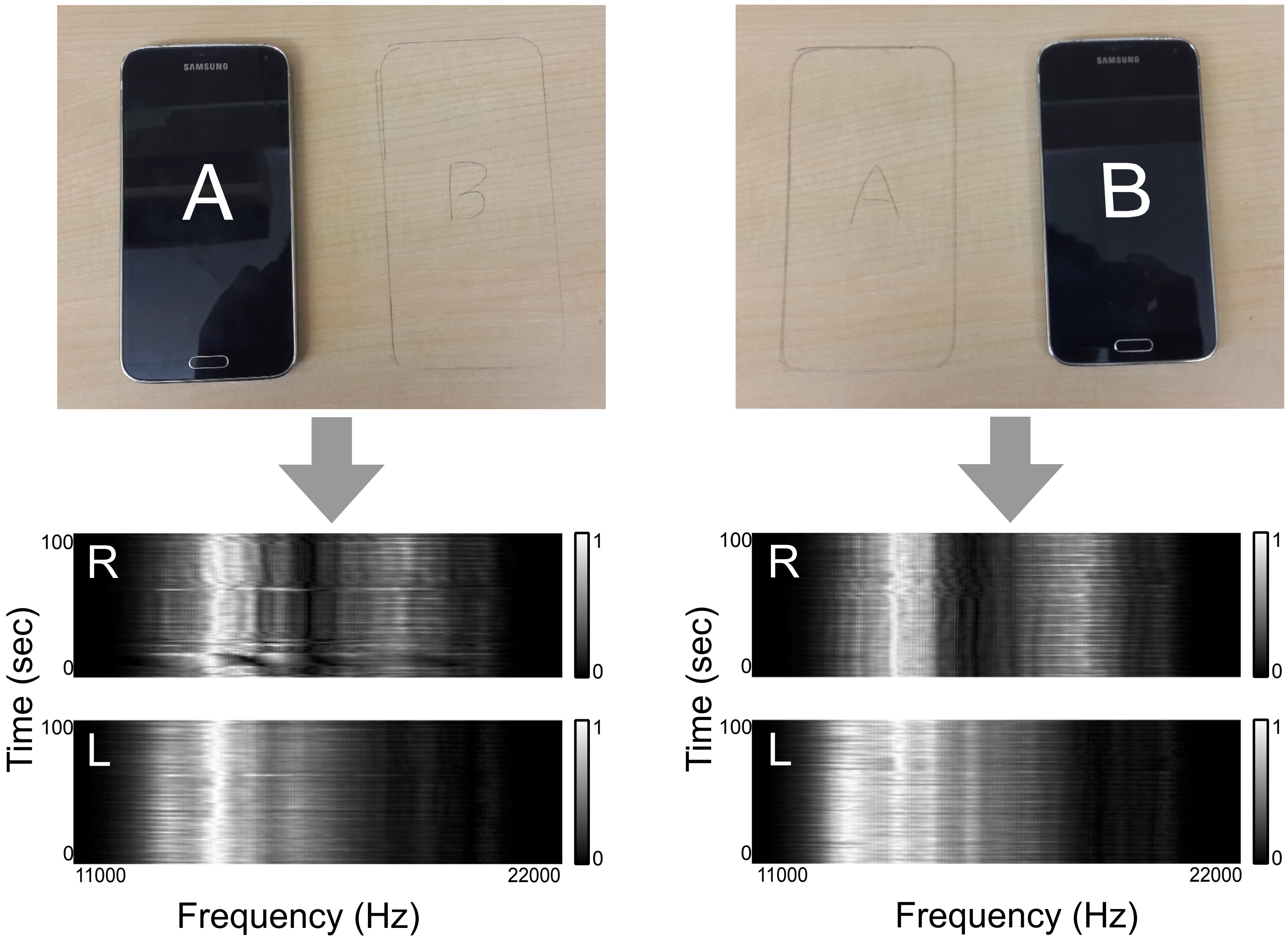
(a) Hardware imperfection

(b) Surface absorption

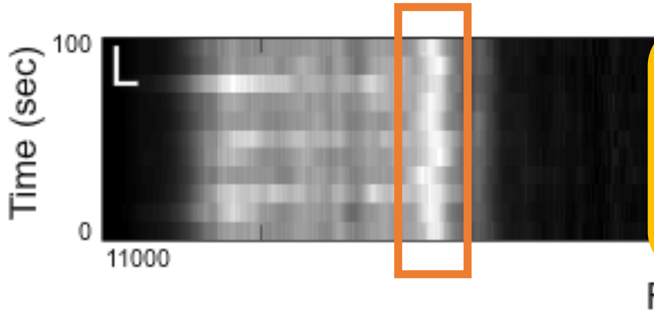


(c) Multipath fading by reflections from surfaces and near objects

Sound Fingerprint – Example

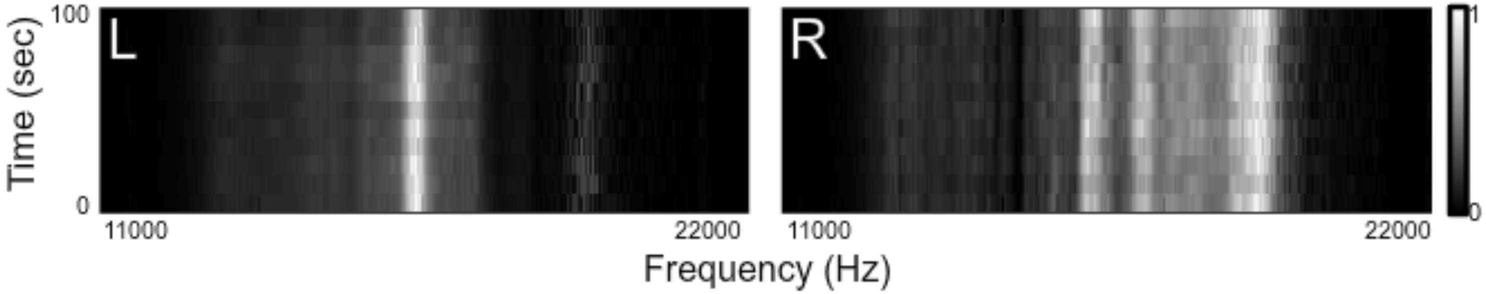


Volumn Control

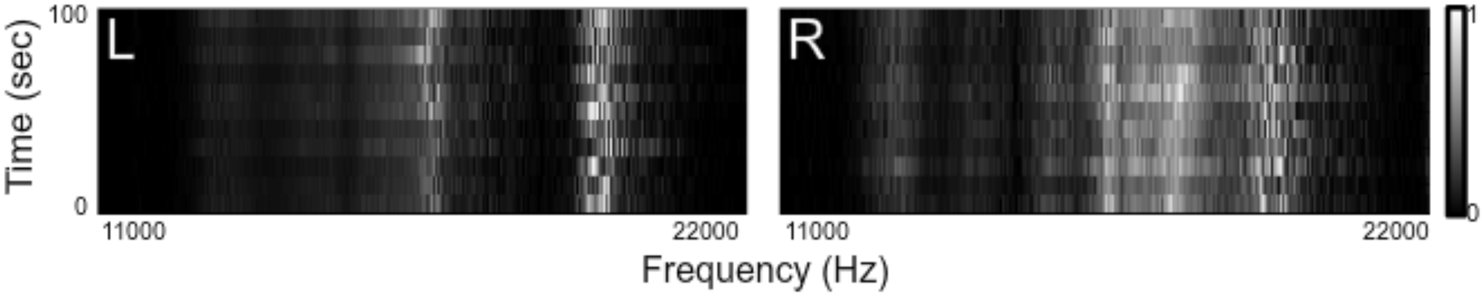


Similar to the linearity problem in WiFi

(a) 100% volume



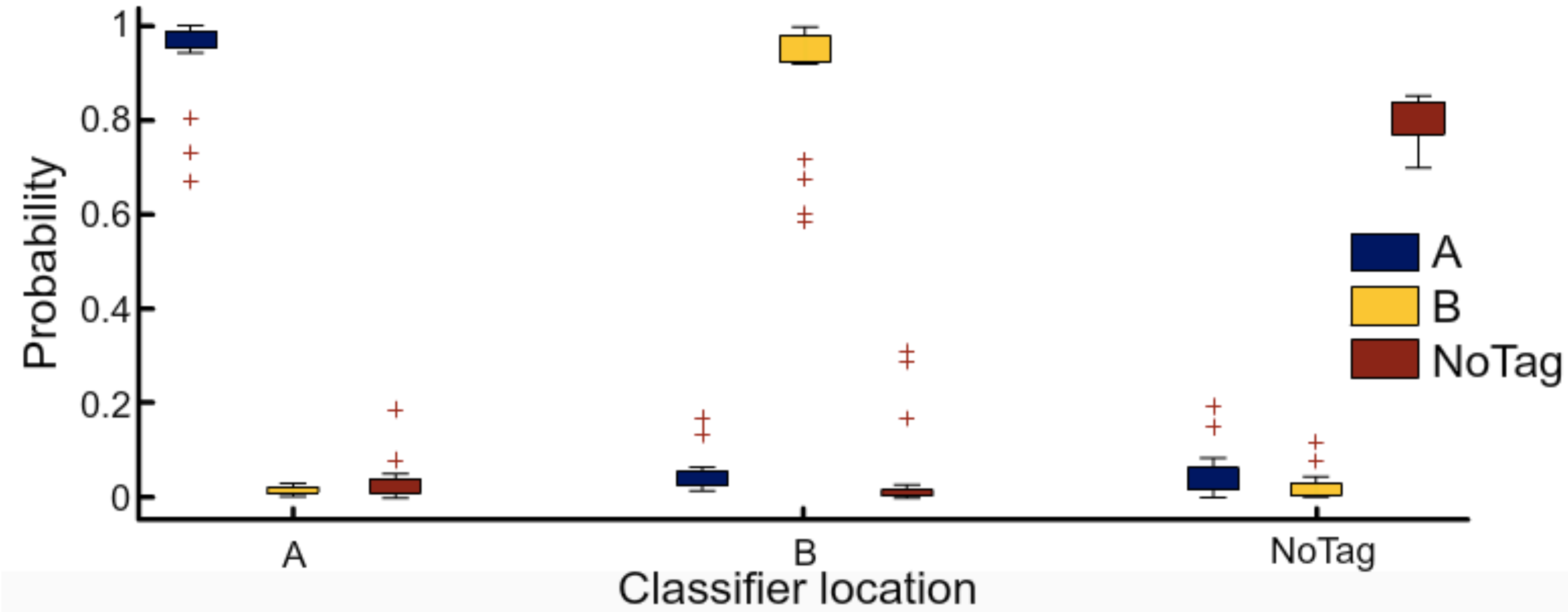
(b) 5% volume



(c) 1% volume

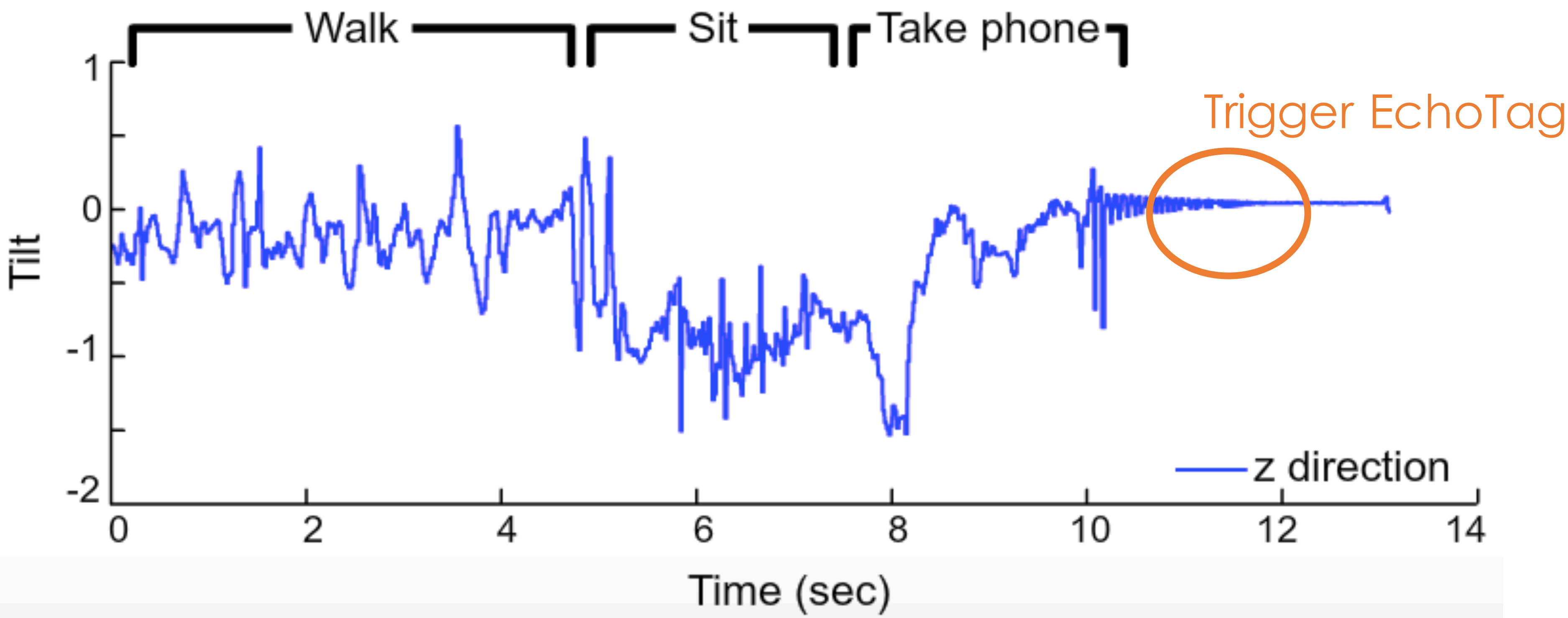
Classification

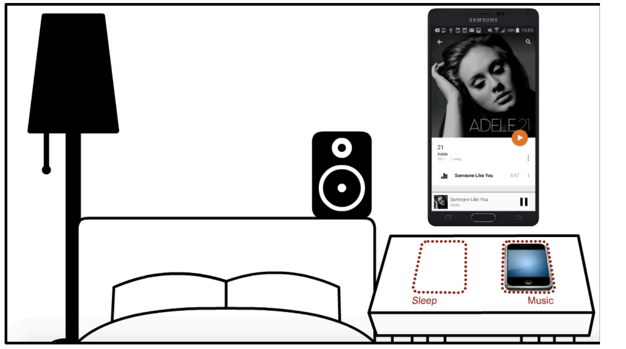
- Support Vector Machine (SVM)
  - One-against-all multi-class SVM
  - NoTag Classifier



Sensing Optimization

- Acoustic sensing is triggered selectively
  - Save energy and reduce annoyance
  - Based on WiFi beacons and tilt





FCC

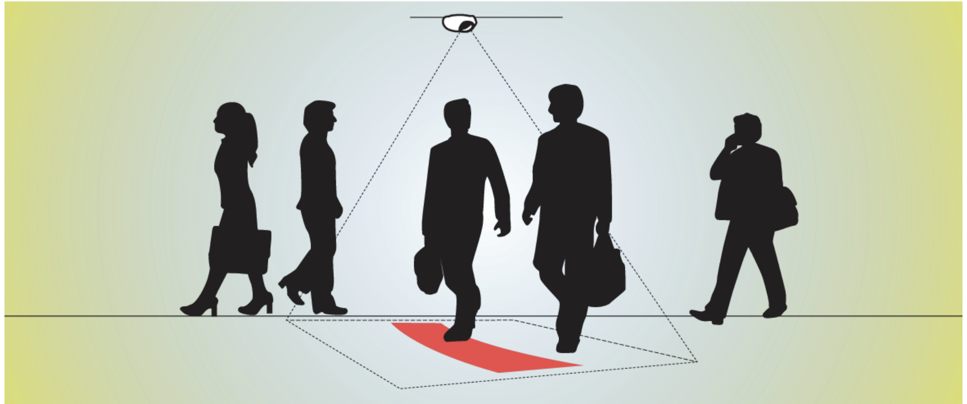
Electronic Frog Eye: Counting Crowd Using WiFi

[INFOCOM'14]

Wei Xi, Jizhong Zhao, Xiang-Yang Li, Kun Zhao, Shaojie Tang, Xue Liu, Zhiping Jiang

Xi'an Jiaotong University, Tsinghua University, Illinois Institute of Technology, Temple University, McGill University

People Counting



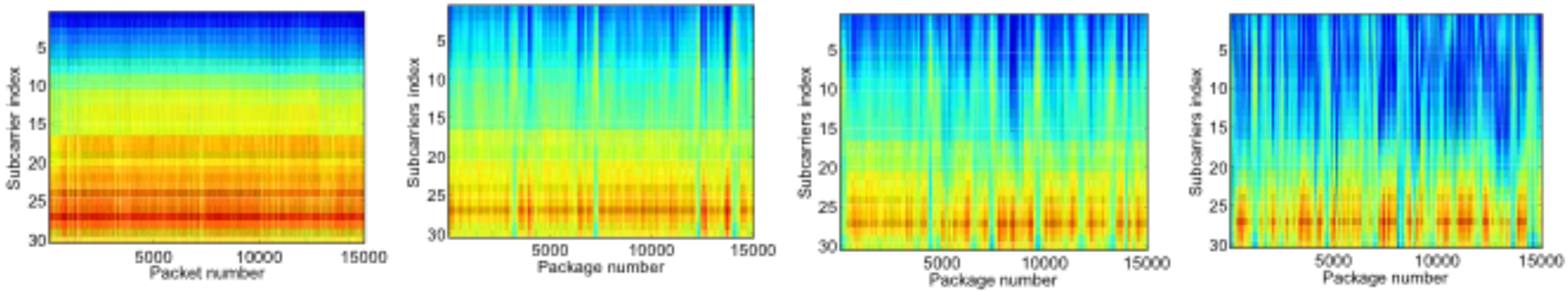
http://www.axis.com/dk/en/solutions-by-application/people-counting

- Application
  - Crowd control, marketing research, etc
- Existing solutions
  - Camera-based: line-of-sight limitation, lighting requirement, vulnerable to object overlap, privacy concern
  - Device-based (RFID tags, sensors, mobile phones): not scalable, high deployment cost

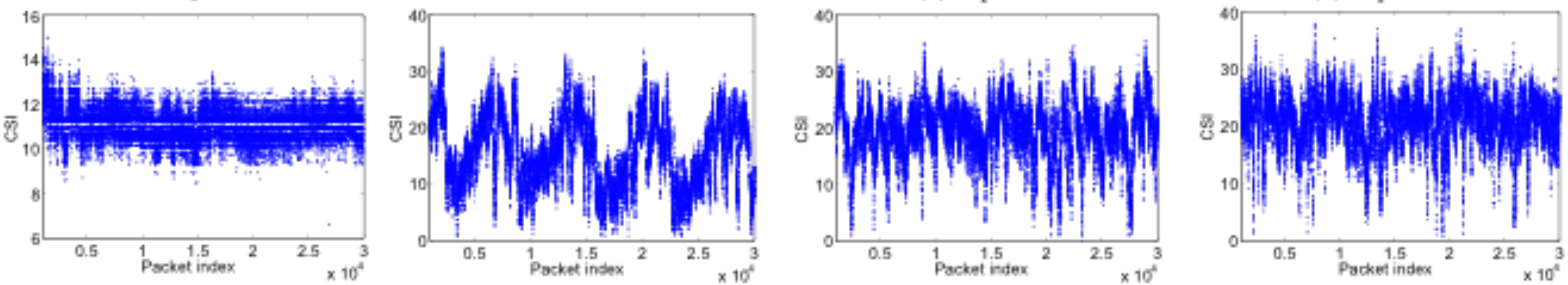
Device-free RF-based Counting

- RSS-based
  - Leverage attenuation models to localize users
  - Poor performance in a multipath-rich environment
- PHY-based
  - Exploit raw physical-layer information
  - Need special hardware, such as USRP
- CSI-based
  - Use fine-grained channel state information (attenuation and phase information of OFDM subcarriers)
  - Can be captured by commodity NICs

Key Idea:
of People vs. CSI Variance



(a) 0 person (b) 2 persons (c) 4 persons (d) 6 persons



(a) 0 person (b) 2 persons (c) 4 persons (d) 6 persons

More mobile users → Higher CSI variation

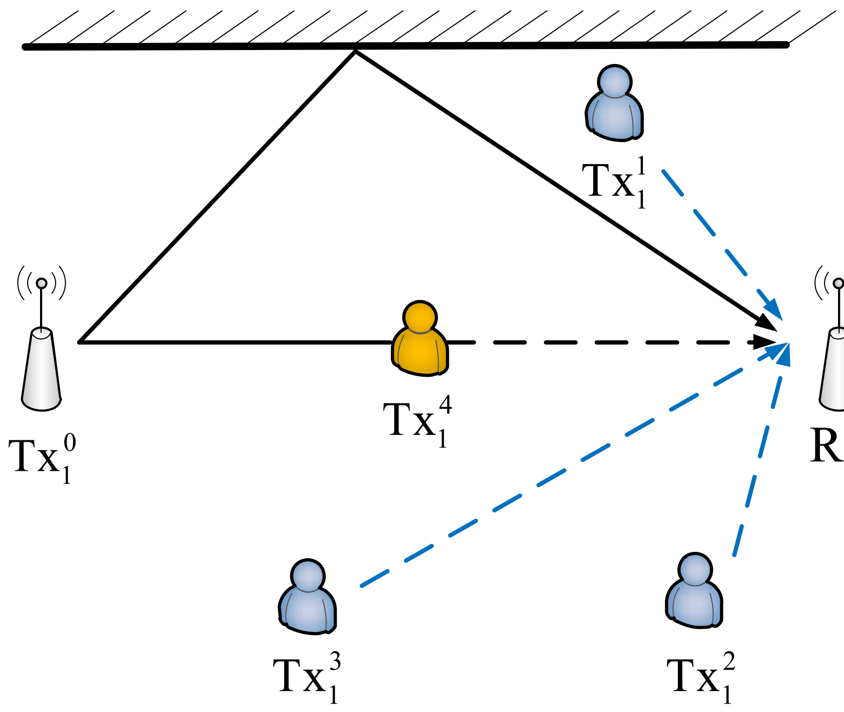
Why?

- Each user can be regarded as a virtual antenna, which reflects the signal toward Rx

$$Y = Y_{static} + Y_{from\_user}$$
$$= HX$$

→ $H = H_{static} + H_{from\_user}$
$$= H_{static} + \sum_{u=1..N} H_u$$

N↑ ⇔ Var(H)↑

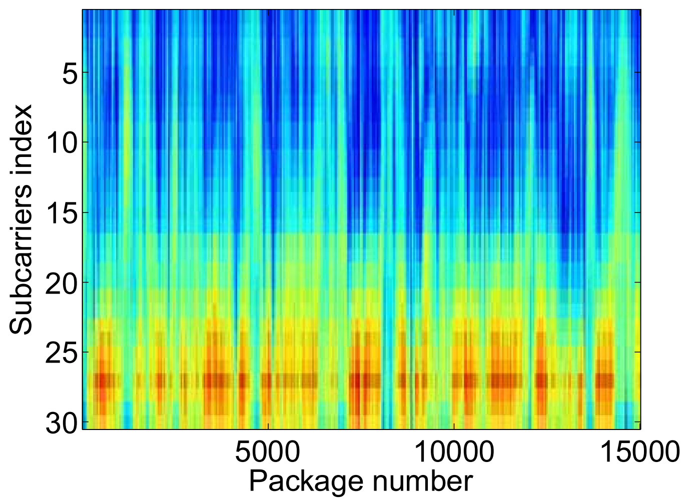


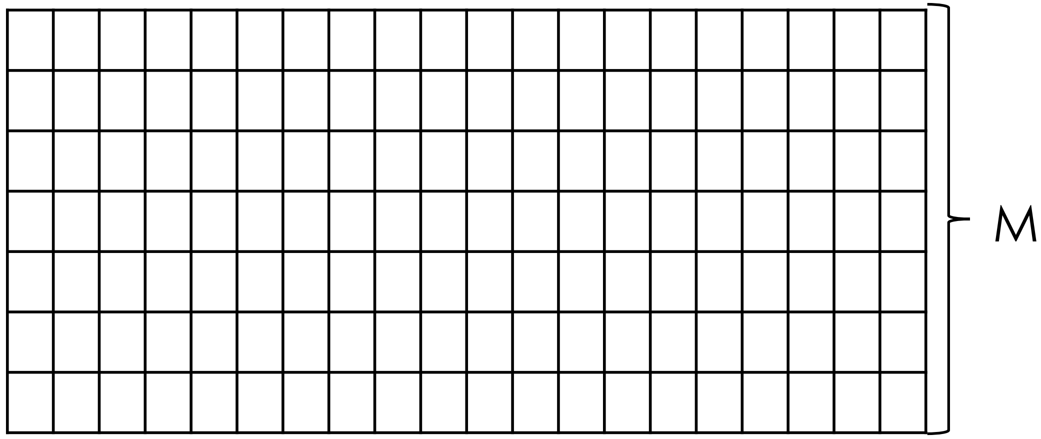
Challenge

- Why it is difficult?
  - Should be resistant to environmental changes
  - But sensitive to human motion i
- Need to learn “short-term” CSI variance
  - Long-term average variance is helpless when the crowd number changes frequently
- Problem: How to get short-term variance when the sample size is small?

PEM

- Percentage of non-zero element in the dilated CSI matrix



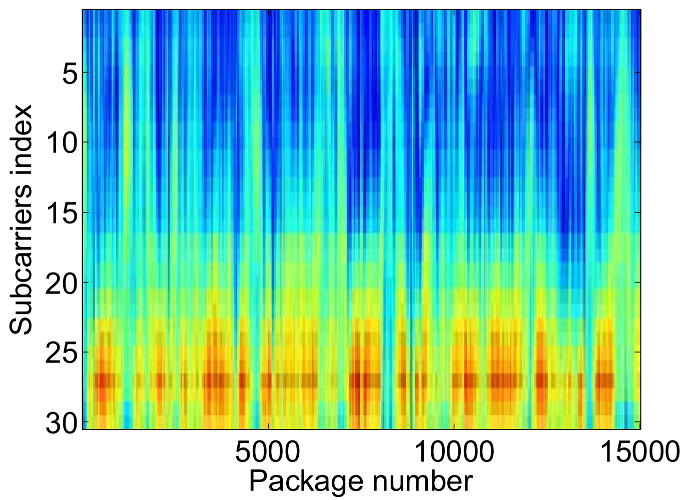


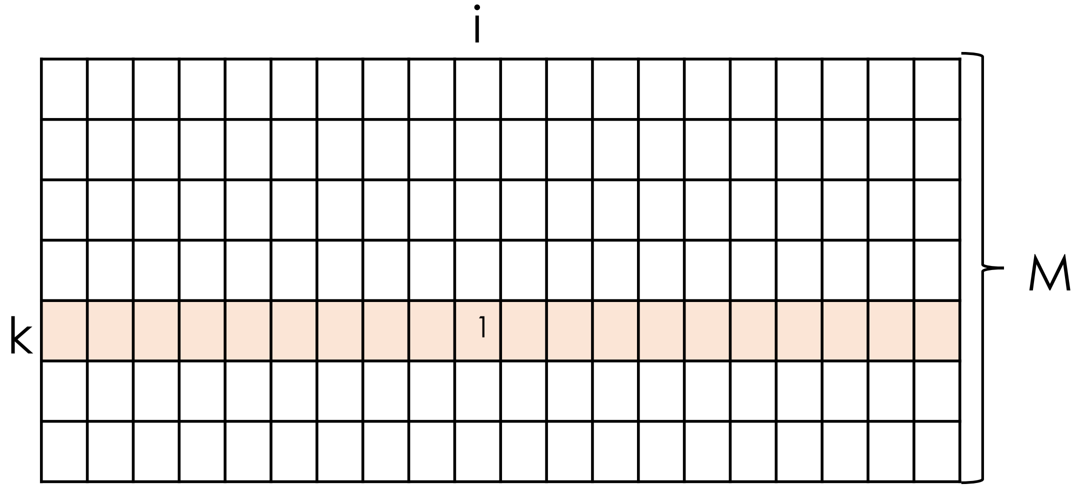
Normalize $|h_{ij}|$ to (h_{min}, h_{max})

$$k = (|h_{ij}| - h_{min}) / (h_{max} - h_{min}) * M$$

PEM

- Percentage of non-zero element in the dilated CSI matrix





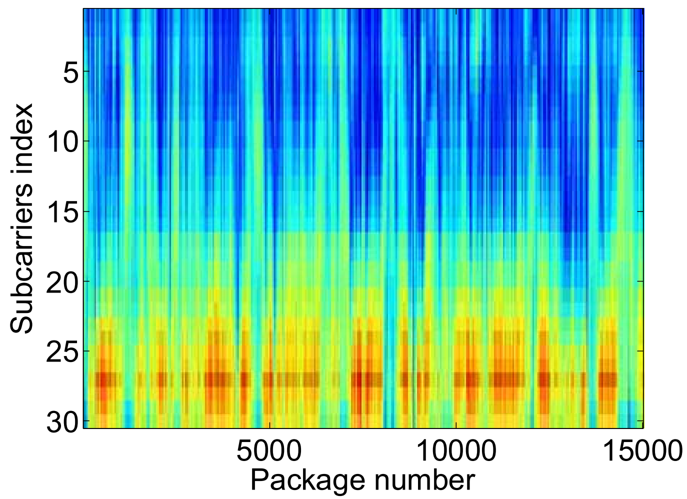
Normalize $|h_{ij}|$ to (h_{min}, h_{max})

$k = (|h_{ij}| - h_{min})/(h_{max} - h_{min}) * M$ → set M[k][j]=1

PEM

Var(H)↑ ⇔ #(1)↑

- Count the percentage of non-zero elements



1		1		1		1			1		1	1		1		1		1	1
1		1			1			1					1		1		1		1
	1		1	1			1	1	1	1	1	1	1				1	1	
1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
	1	1			1	1	1		1		1		1		1		1	1	1
1	1	1	1		1		1	1		1		1		1		1	1		1
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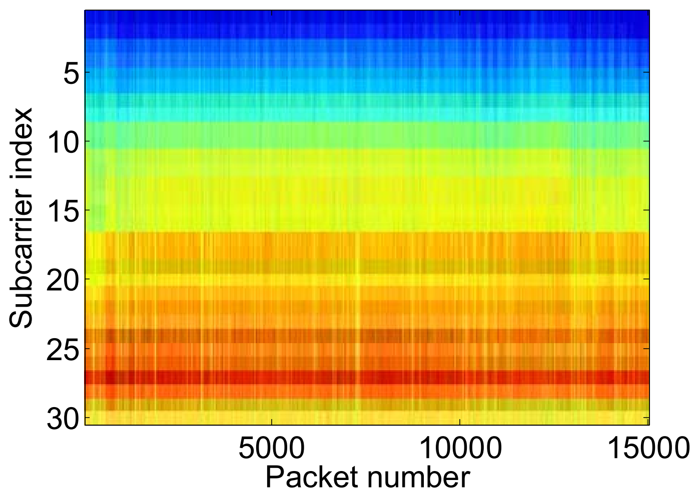

							1	1					1			1		1	
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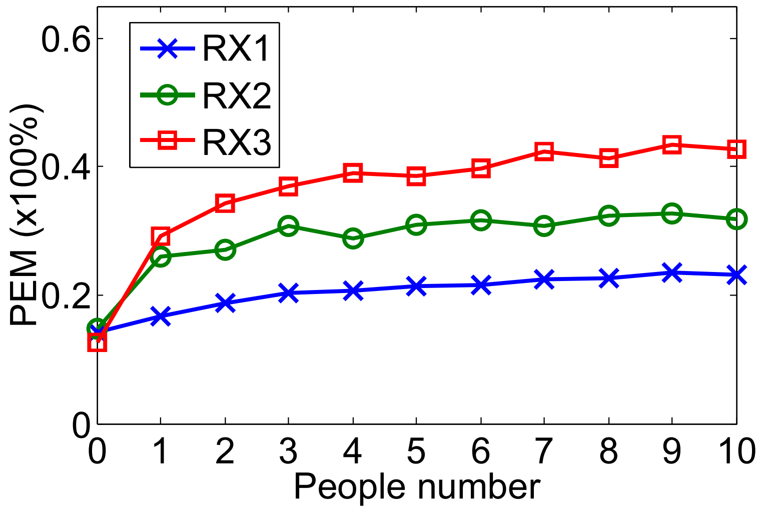
1	1	1		1	1	1		1	1		1	1			1		1		1
1			1		1	1	1			1		1		1				1	
	1						1	1		1	1		1			1	1		1

Map PEM to Number of People

- Use fringerprint to find the relationship between PEM and people number



Quasi-monotonous relationship

- How to use fewer samples (less effort of measurements) to find the fitting curve?
  - Verhulst model (check the paper)