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WiDance:
Inferring Motion Direction using Commodity Wi-Fi for Interactive Exergames

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Exergames bring more than just fun

- Exergames can improve the fitness, health and social involvement of players

Becoming increasingly popular!
Exergames anywhere, anytime!

Various Exergame Interfaces

- Various technologies for interactive exergames

Computer Vision

Sensors & Controllers

Ultrasound

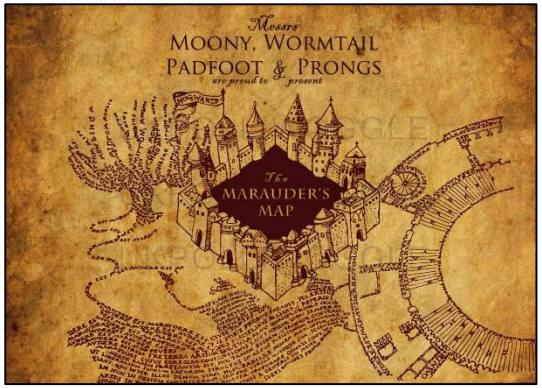
Limitations

- Limited field of view
- Device attachment
- Dedicated devices
- High installation cost
- Usually expensive
- Not ubiquitous

Demand for a more ubiquitous solution to fit fragmented free time and space for modern life

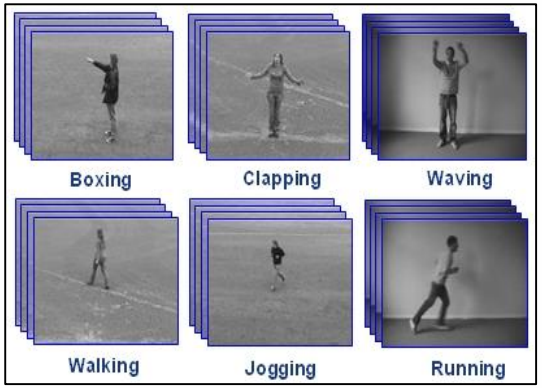
Leveraging Commodity WiFi

- In contrast, the wireless approach is superior in
  - **Ubiquitous**: Almost everywhere installed infrastructure
  - **Low-cost**: off-the-shelf WiFi devices
  - **Non-invasive**: not required to wear/carry any devices
  - Omi-directional & no lighting requirement
- WiFi-based sensing supports more than exergame



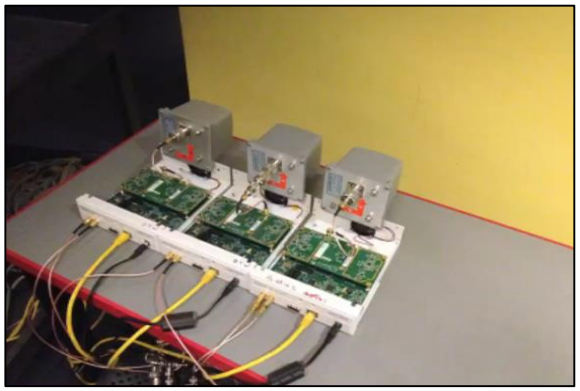
Navigation

Gait Analysis



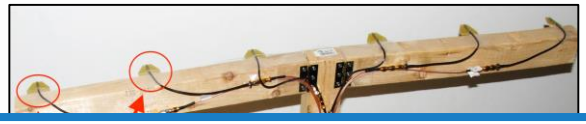
Activity Recognition

Existing Arts



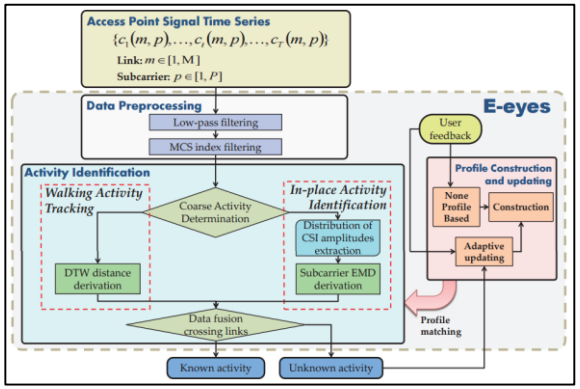
WiVi, Sigcomm '13

WiSee, Mobicom '13

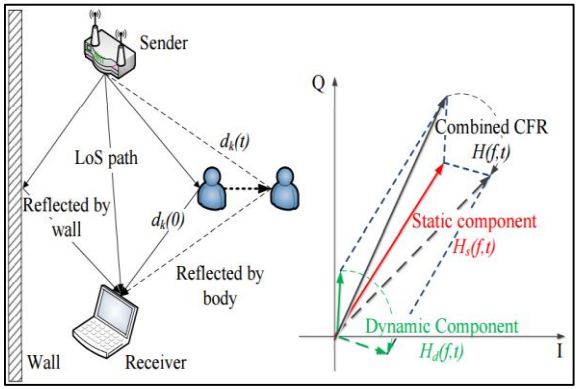


They estimate precise signal parameters, yet rely on specialized hardware!

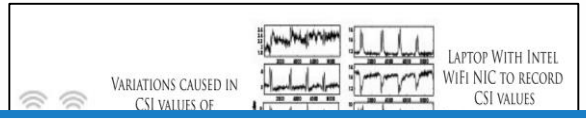
Existing Arts



E-eye, Mobicom '14



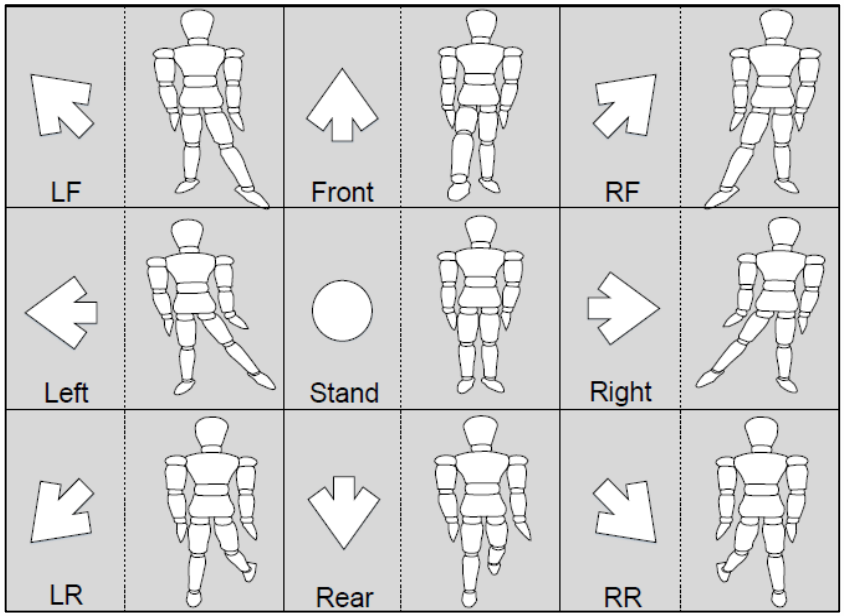
CARM, Mobicom '15

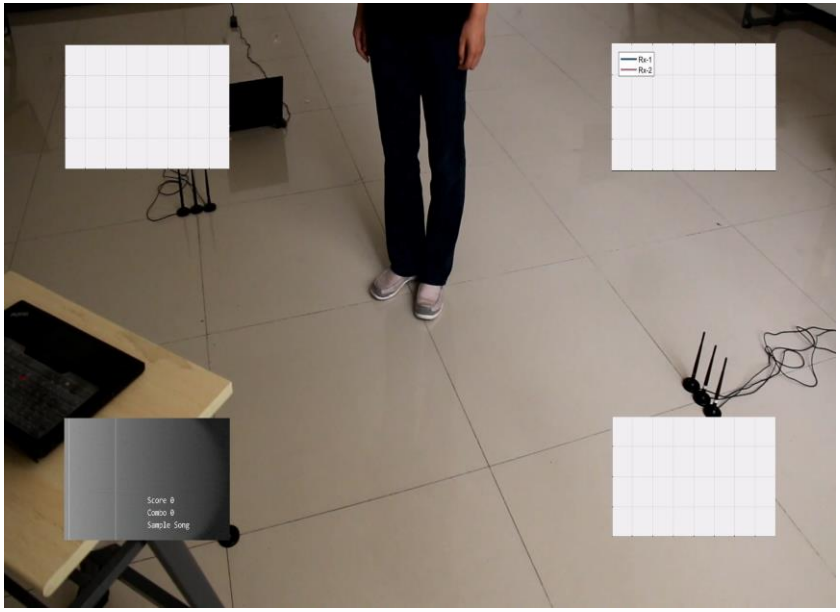


Though using COTS Wi-Fi, they require extensive training efforts.

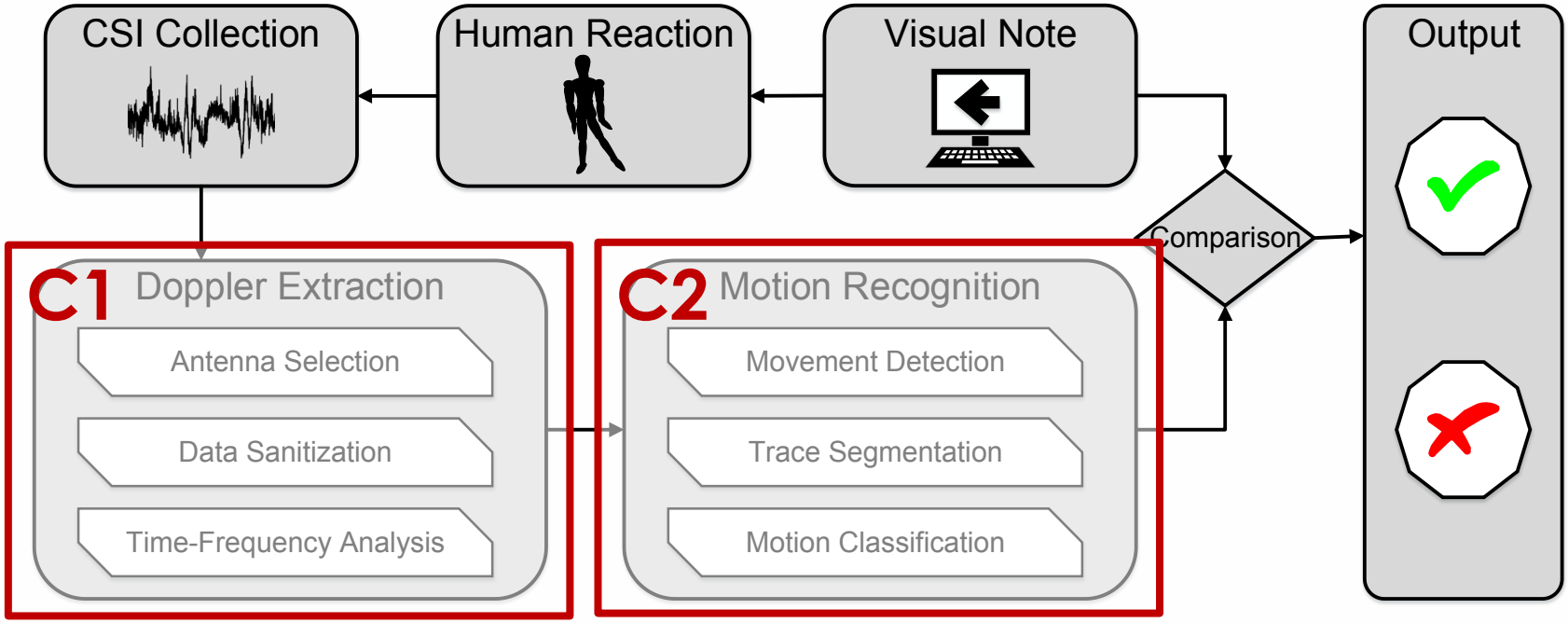
WiDance

- A passively interactive dancing pad-like exergame using **OFF-THE-SHELF** WiFi devices **WITHOUT** training
  - Accurately deriving motion-induced Doppler shifts
  - Extracting motion directions for exergame designs





WiDance Design

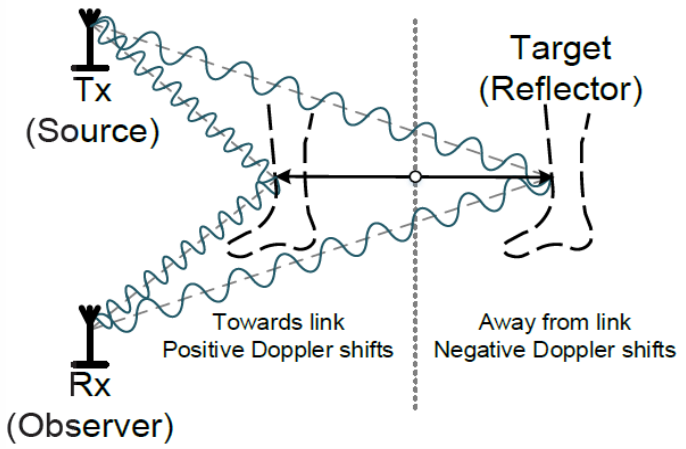


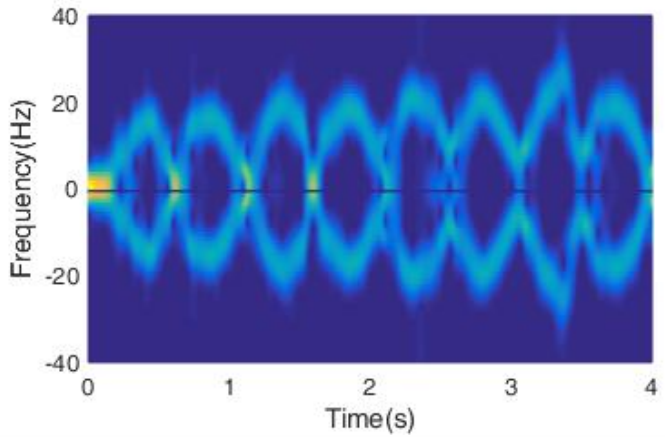
Two key challenges

- Derive **full information** of Doppler shifts from **imperfect** Wi-Fi.
- Recognize motion direction from Doppler effect for game.

Doppler Effects

- Human motions induce Doppler shifts in signals





COTS WiFi Devices

Channel State Information

$$H(f,t) = H_s(f) + \sum_{k \in P_d} \alpha_k(t) e^{j2\pi \int_{-\infty}^{t} f_{D_k}(u)\mathrm{du}}$$

Doppler Freq. Shifts

- However, due to **uncertain phase noise**, only **absolute values** are available by using CSI power [1]

[1] CARM, Mobicom '15

Doppler Extraction

- Remove unknown phases with multiple antennas
- Conjugate multiplication of signal of **TWO** antennas

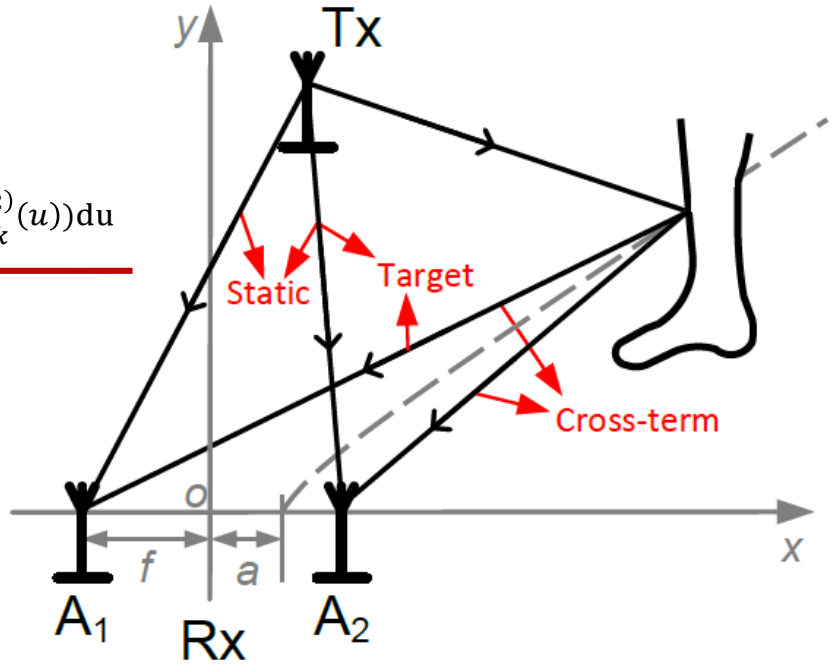
$$H^{(1)}(f,t)H^{(2)}(f,t)^*$$

$$\approx H_s^{(1)}(f)H_s^{(2)}(f)^* \longrightarrow \text{Static term}$$

$$+ \sum_{k\in P_d^{(1)}, l\in P_d^{(2)}} \underbrace{\alpha_k^{(1)}(t)\alpha_k^{(2)}(t)^* e^{j2\pi \int_{-\infty}^{t}\left(f_{D_k}^{(1)}(u)-f_{D_k}^{(2)}(u)\right)\mathrm{du}}}_{\text{Cross term}}$$

$$+ \sum_{k\in P_d^{(1)}} \underbrace{\alpha_k^{(1)}(t)H_s^{(2)}(f)^* e^{j2\pi \int_{-\infty}^{t} f_{D_k}^{(1)}(u)\mathrm{du}}}_{\text{Target term}}$$

$$+ \sum_{k\in P_d^{(2)}} \underbrace{H_s^{(1)}(f)\alpha_k^{(2)}(t)^* e^{j2\pi \int_{-\infty}^{t} -f_{D_k}^{(2)}(u)\mathrm{du}}}_{\text{Target term}}$$



Yet Target terms contain both $f_{D_k}^{(1)}$ and $-f_{D_k}^{(2)}$!

Doppler Extraction

- A sufficient condition is the term with true Doppler frequency shift has higher power

$$\left|\frac{H_s^{(1)}(f)}{\alpha_k^{(1)}(t)}\right| < \left|\frac{H_s^{(2)}(f)}{\alpha_k^{(2)}(t)}\right|$$

$=$

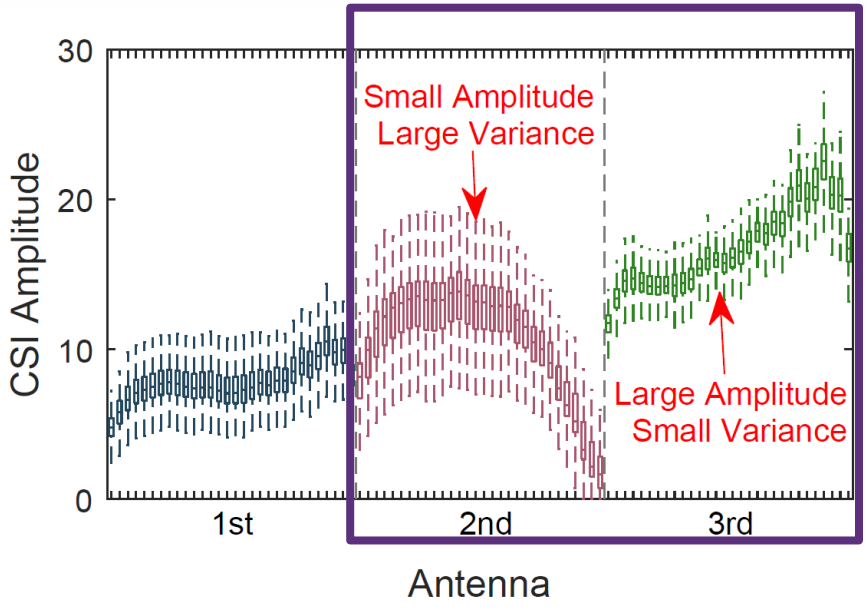
$$\frac{\text{Static component \#1}}{\text{Dynamic component \#1}} < \frac{\text{Static component \#2}}{\text{Dynamic component \#2}}$$

$\approx$

$$\frac{\text{Mean of power \#1}}{\text{Std of power \#1}} < \frac{\text{Mean of power \#2}}{\text{Std of power \#2}}$$

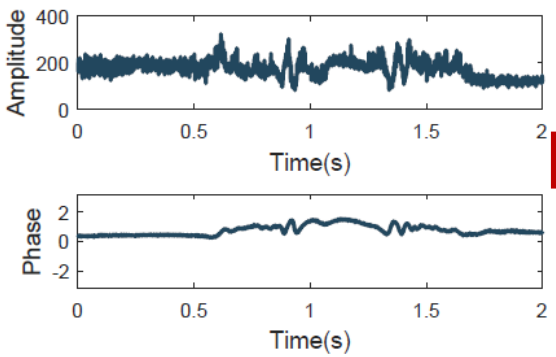
Antenna Selection

- Select two antennas out of the typical three.
  - Antenna #1: Small Amplitude, Large Variance.
  - Antenna #2: Large Amplitude, Small Variance

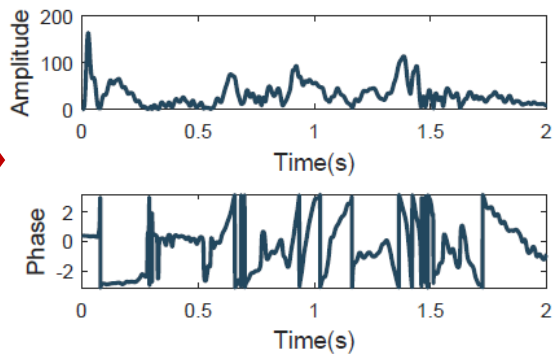


Signal Processing Procedure

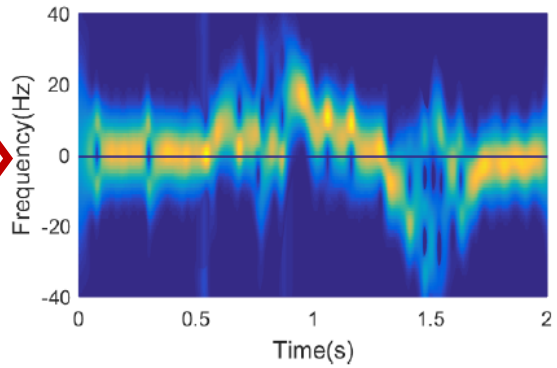
- Passband filtering
  - Remove static terms, low-frequency interferences and burst noises.
- Time-Frequency Analysis (PCA + STFT)
  - Spectrogram of Doppler frequency shifts.



Raw signal

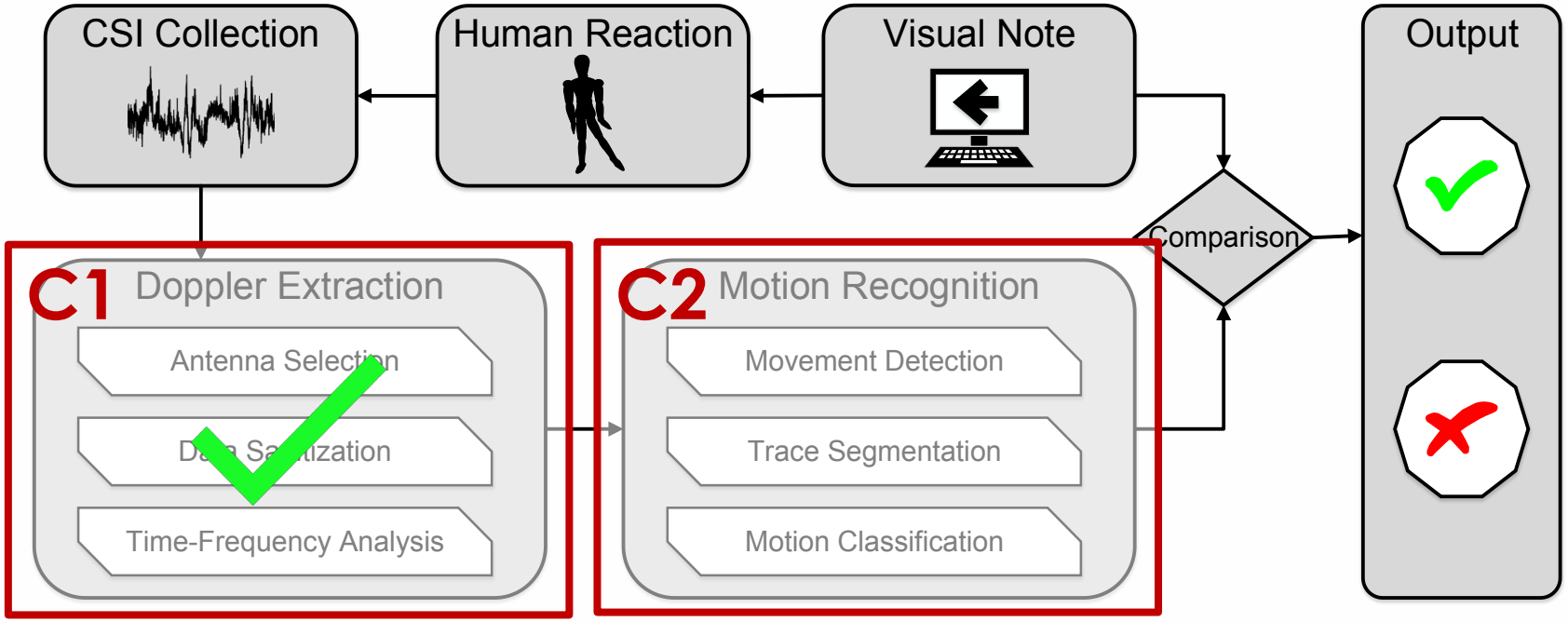


Passband Filtering



Spectrogram

Problem Statement



- Challenges
  - Derive motion-induced Doppler frequency shifts from Wi-Fi.
  - **Recognize motion direction from Doppler effect for game.**

Motion Recognition

- One link is insufficient for direction recognition.

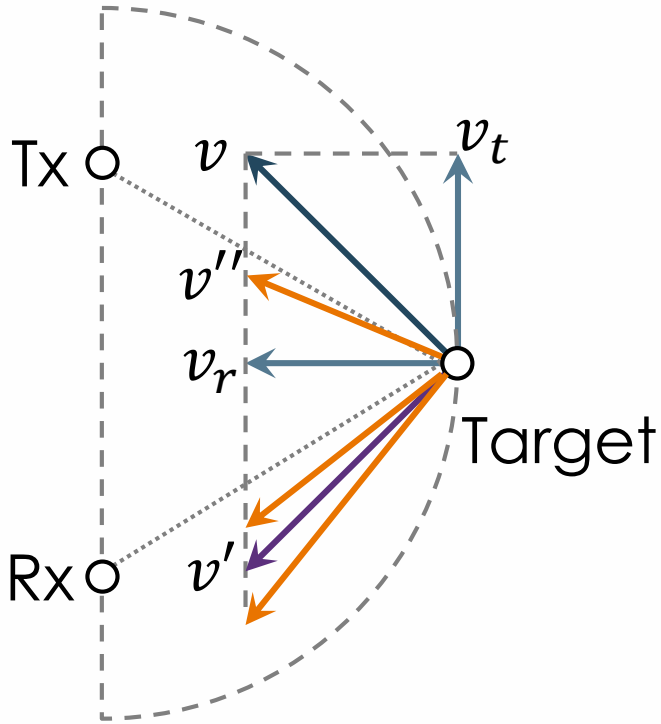
Infinite possible solutions of v

× The symmetric distribution of radial velocity

v VS. v'

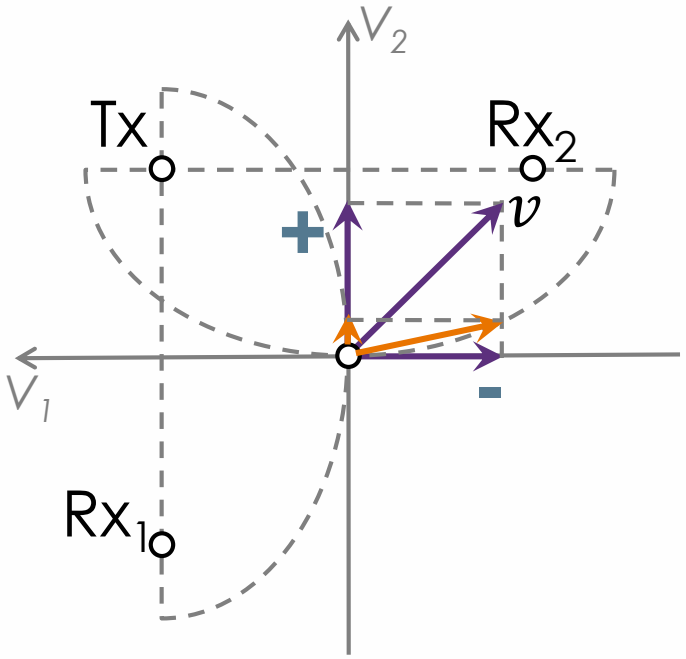
× Users perform reactions at unknown speed

v VS. v''



Motion Recognition

- Solve ambiguity with minimum cost of two orthogonal links.

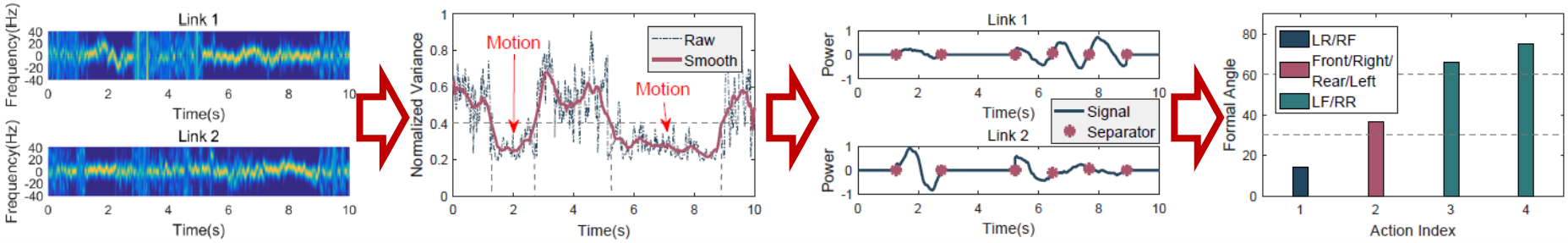


Determine the motion direction by:

- **Direction of radial velocity.**
- **Ratio of radial velocity.**

Motion Recognition

- Movement Detection
  - Distribution of signal power in frequency domain.
- Trace Segmentation
  - Detection of pair of prominent peaks
- Motion Classification
  - Direction of radial velocity.
  - Ratio of radial velocity.



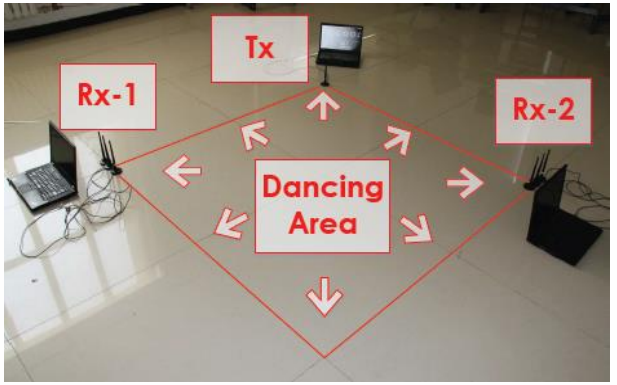
Spectrogram Detection Segmentation Classification

Experiment & Evaluation

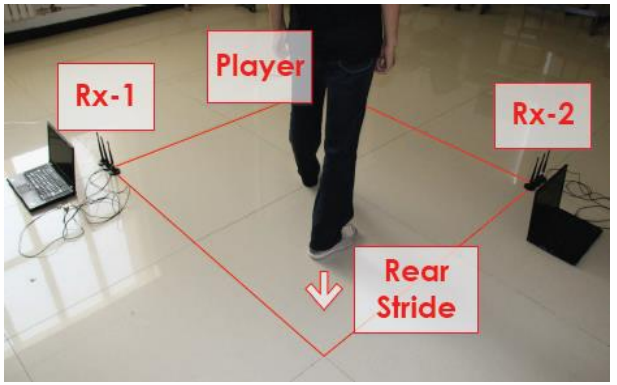
- Overall performance
- Performance of recognition scheme
- Performance of extraction scheme
- Performance of compound gestures
- Performance comparison
- Impact of user diversity
- Impact of action range
- Impact of note interval
- Impact of area size
- Impact of transmission rates

Experiment

- Setup
  - 3 laptops with Intel 5300 NICs.
  - 2 links on Channel 165 (5.825GHz).
  - Packet rate: 1024Hz.
  - Tx power: 15dBm.
- Recruitment
  - 30 participants.
  - Over 10, 000 actions.
- Baselines
  - HMM-WiDance
  - CARM (ACM MobiCom'15)



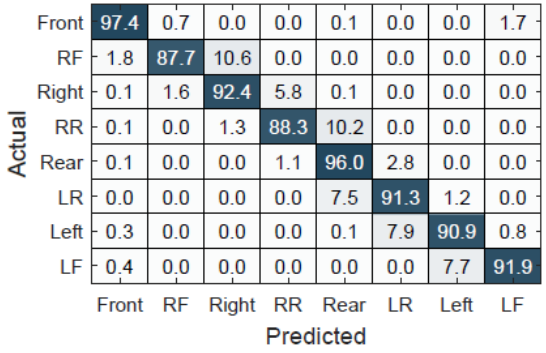
Dancing Area



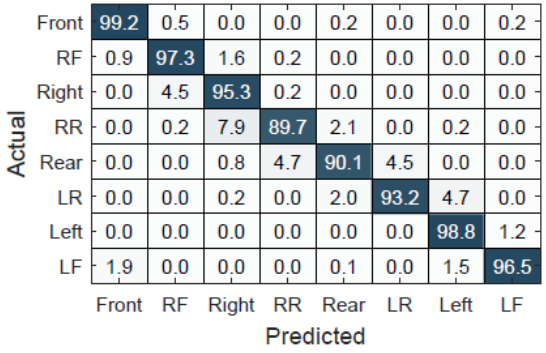
User Action

Overall Performance

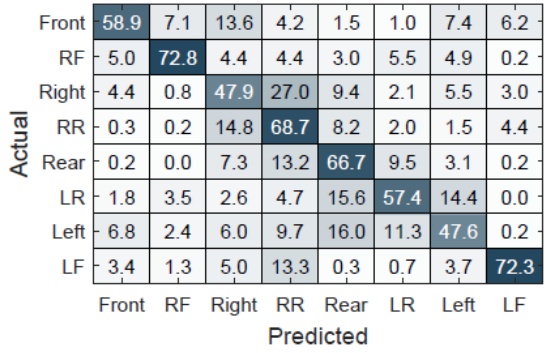
- WiDance vs. HMM-WiDance
  - Non-learning recognition scheme achieves comparable accuracy with the unfavorable learning method.
- WiDance vs. CARM
  - Only with both amplitude and sign of Doppler frequency shifts can motion directions be effectively recognized.



WiDance (Overall 92%)

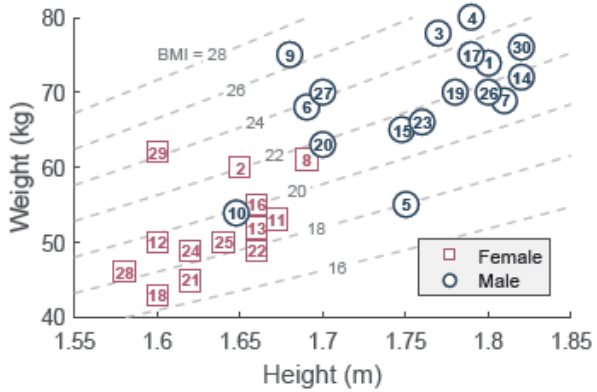


HMM-WiDance (Overall 95%)

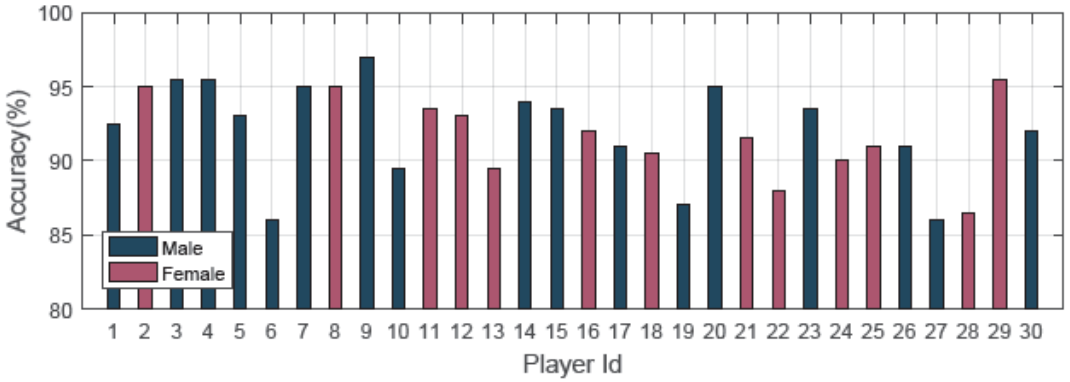


CARM (Overall 60%)

Impact of User Diversity



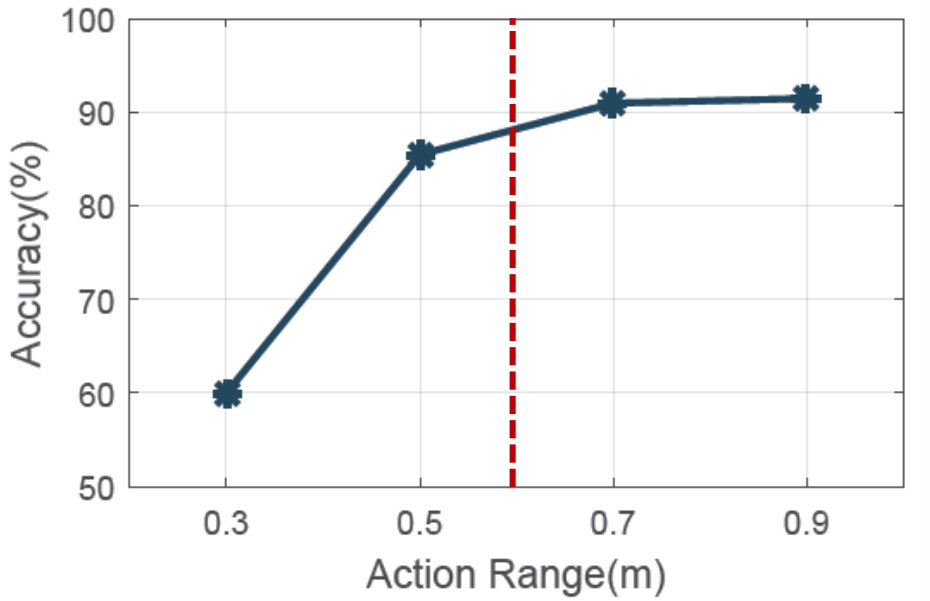
Participants status



Impact of user diversity

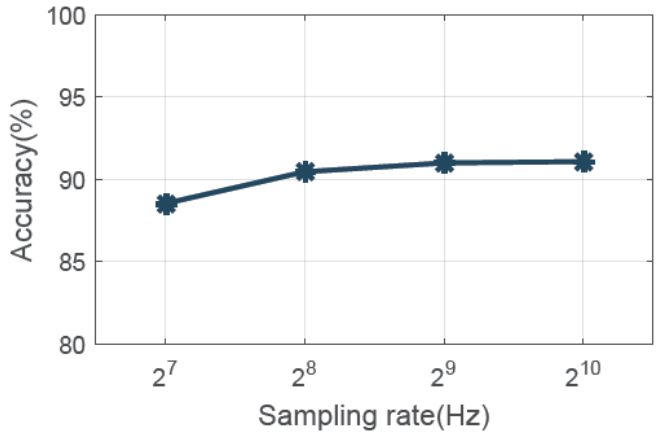
- Participants have various weights and heights
- And different levels of body coordination and familiarity with dancing games
- WiDance recognizes actions of all participants with accuracy higher than 85%

Impact of Action Range

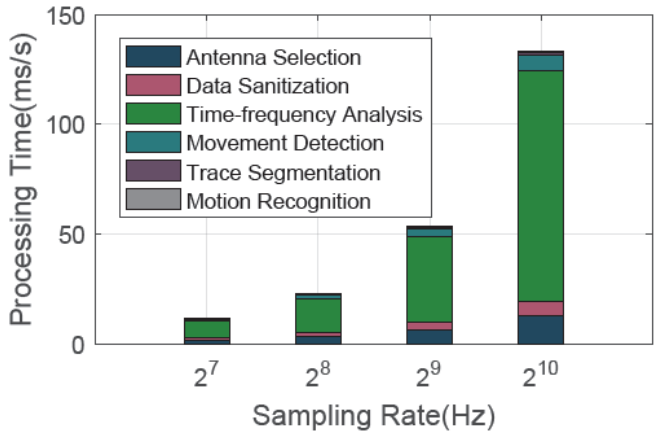


- Smaller action ranges leads to
  - shorter action time
  - smaller action speed
- >90% when the action range is larger than 0.6m

Impact of Packet Rate



Impact of packet rate



Computation Overhead

- With decreasing of transmission rate,
  - Accuracy of WiDance slightly degrades.
  - Processing time of WiDance exponentially reduced.
- Tradeoff processing time and accuracy

Discussion

- Multiple moving objects.
  - Doppler shift of the dancer might be obfuscated by the similar shift of the intruder.
- Limited detection range.
  - Currently 4m X 4m, easily deployed at different location
  - Deploying more systems in the area of interest.
- Potential applications.
  - Smart home controller.
  - Indoor localization.

Conclusion

- **Extracting complete Doppler frequency shifts from COTS Wi-Fi.**
  - Doppler effect of multiple antennas.
  - Antenna selection strategy.
- **Recognizing motion directions with Doppler effect.**
  - Orthogonal links model.
  - Light-weight non-learning recognition scheme.
- **A proof-of-concept interactive exergame WiDance.**
  - an overall recognition accuracy of 92% in typical indoor environments without training.

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Thanks!

Q&A

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