Enabling Sensorless Sensing with WiFi Radar

Zheng Yang / 杨铮

School of Software, Tsinghua University

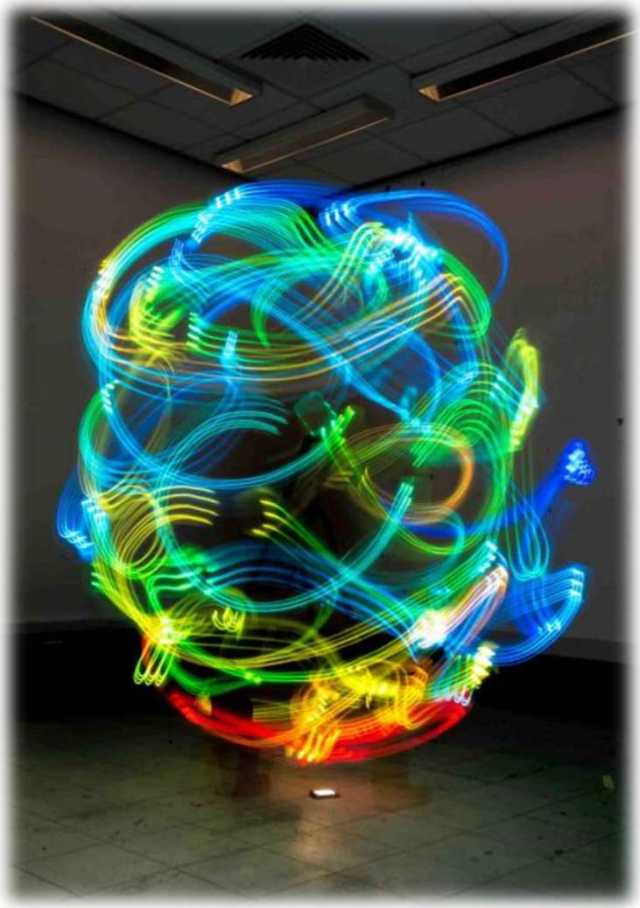
hmilyyz@gmail.com

http://tns.thss.tsinghua.edu.cn/~yangzheng/

Outline

- **Introduction**
- Background
- Methods & Applications
- Conclusion

WiFi Signals Everywhere

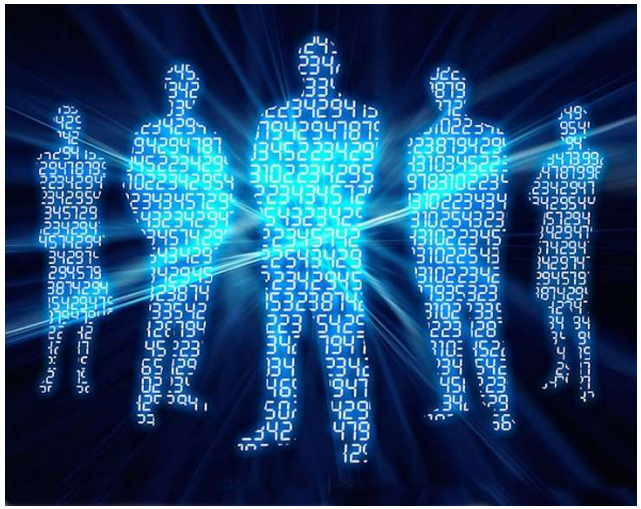


Visualization of WiFi signals by Luis Hernan

WiFi as Radar?

WiFi Radar

Omnipresent Sensing around You



WiFi Radar: Applications

Access Control

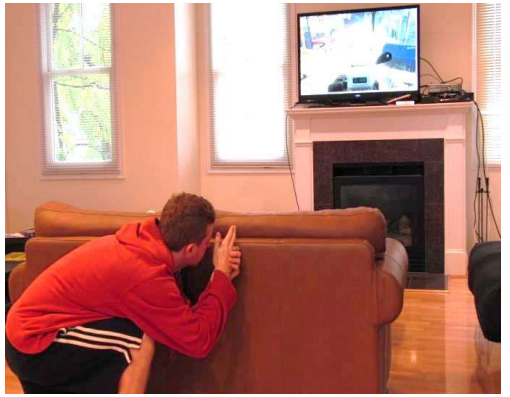
Asset Security

Intrusion Detection

Fall Detection

Sleep Quality Assessment

Healthcare



Whole-home Gaming

Remote Control

HCI

WiFi Radar: Benefits

- **Benefits:**
  - **Wireless** sensing without wires
  - **Sensorless** sensing without dedicated sensors
  - **Contactless** sensing without wearable sensors
  - Through-wall & Privacy Preserving

How to Enable
Sensoreless Sensing with WiFi?

Outline

- Introduction
- **Background**
- Methods & Applications
- Conclusion

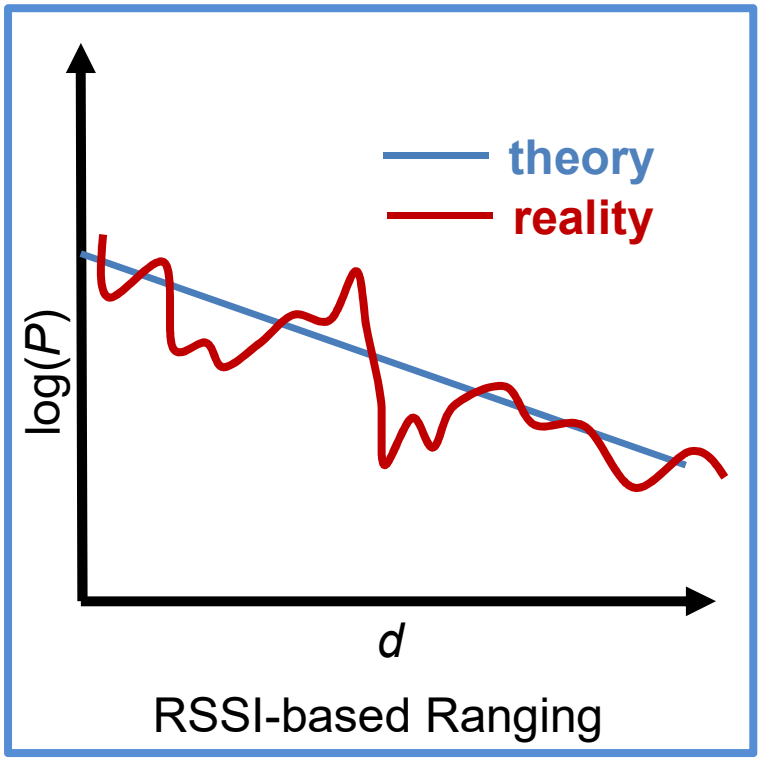
Detect Environment Dynamics

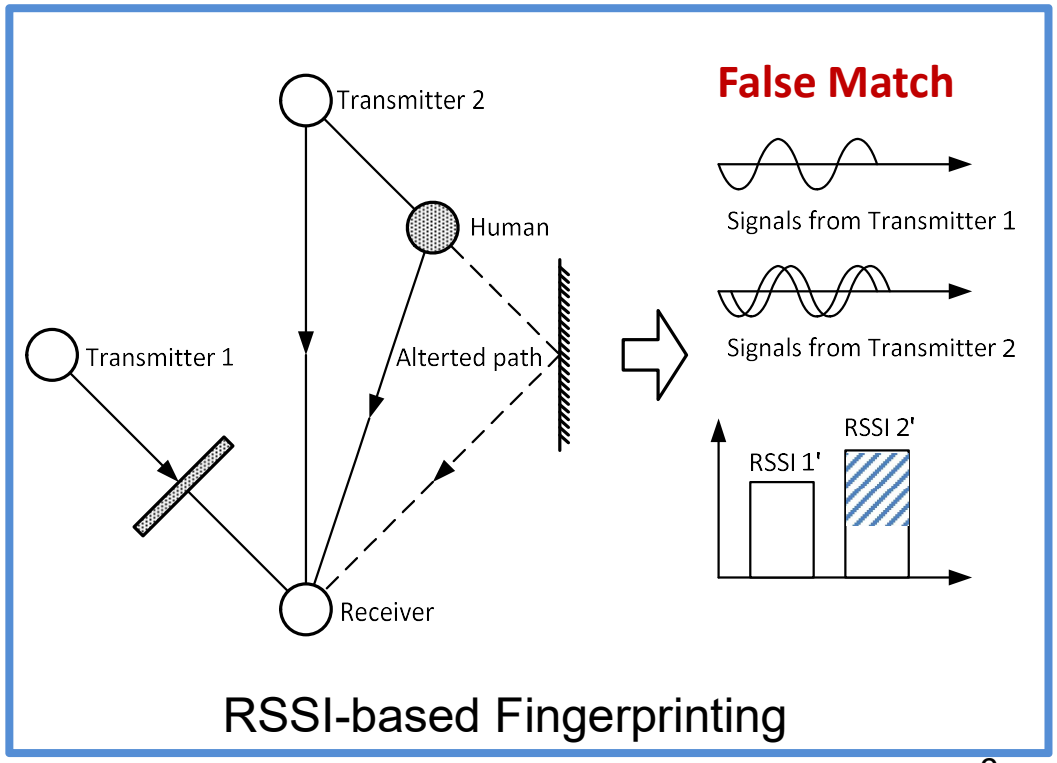
Signal Strength + LED =

- Capture environment dynamics via the fluctuation of radio signal
  - Received radio signal strength (RSSI)
- Is RSSI a Good Signal Feature?
  - In theory, it is. However …
  - In practice, sensing ability of RSSI is greatly weakened by rich multipath effects

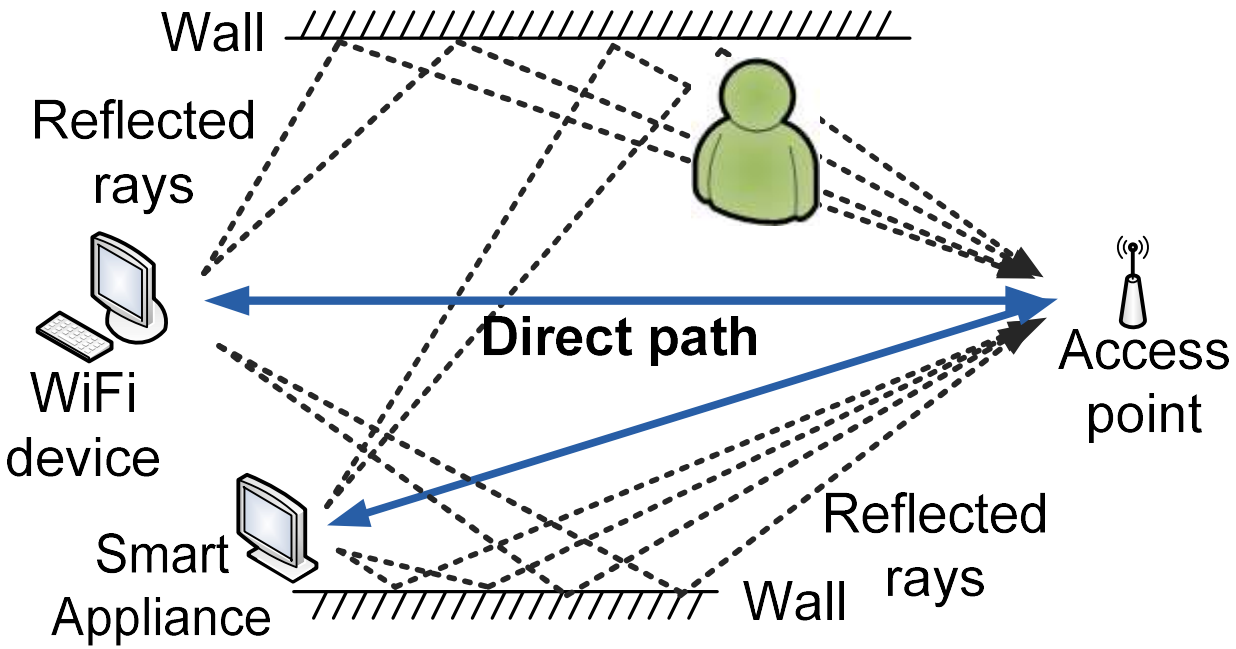
Multipath: Enemy!

- Impacts of Multipath Effects:
  - Bound Accuracy of Ranging
  - Induce False Match in Fingerprinting





Multipath: Friend?!

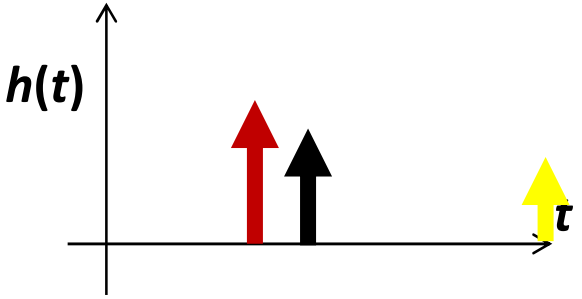


Multipath Propagation Conveys Rich Environment Information

Characterizing Multipath

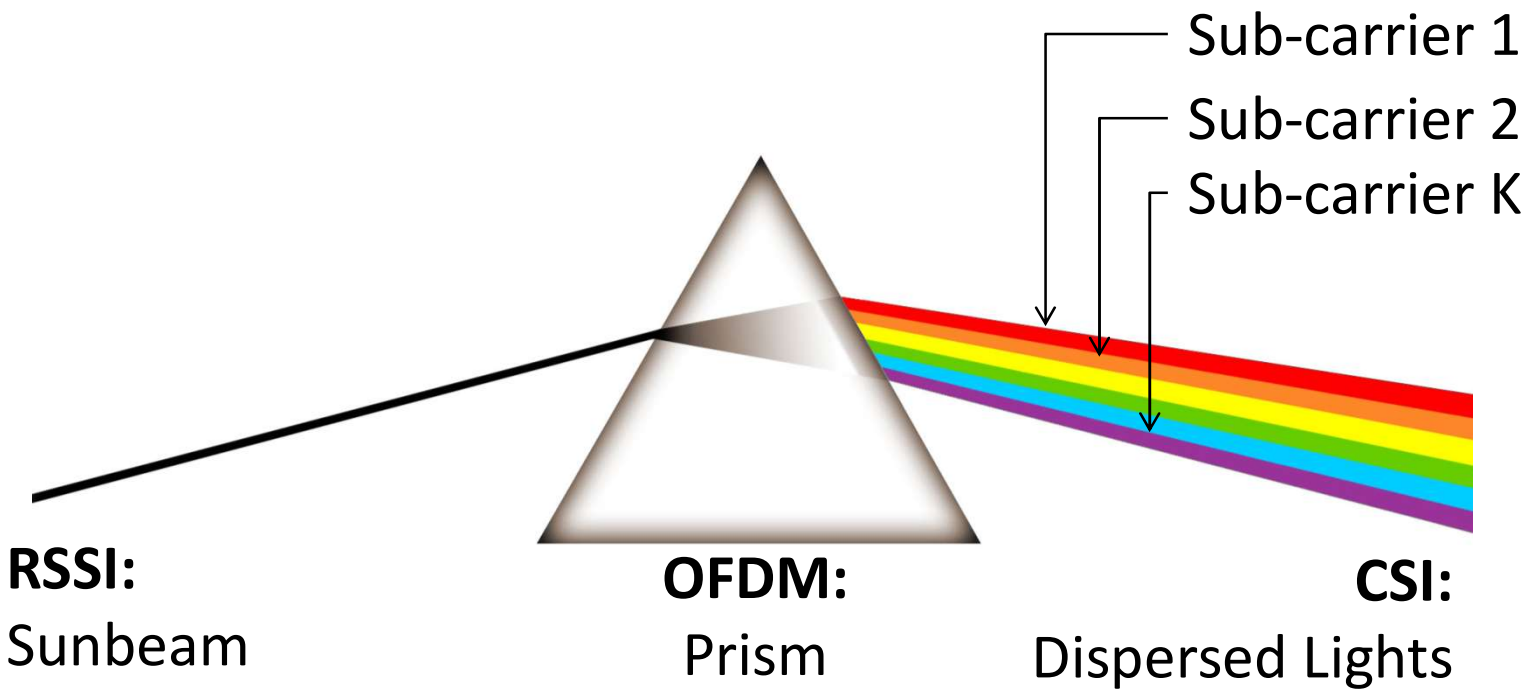
- Channel Impulse Response (CIR)
  - a set of attenuated, delayed impulse functions, depicting multipath

$$h(\tau) = \sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\delta(\tau - \tau_i)$$



- Deriving Channel Response
  - VNA / SDR for precise measurement
  - Channel State Information (CSI): sampled version of channel response with OFDM at sub-carrier level
  - CSI on a single sub-carrier k: $H(f_k) = \left\| H(f_k) \right\| e^{j\sin(\angle H)}$

Channel State Information



- Analogously, CSI is to RSS what a rainbow is to a sunbeam.
  - CSI separates signals of different wavelengths via OFDM
  - RSS only provides a single-valued amplitude of superposed paths.

CSI vs. RSSI

Category	RSSI	CSI
Layering	MAC layer	PHY layer
Time Resolution	Packet level	Multipath clusters
Frequency Resolution	N/A	Sub-carrier level
Stability	Low	High for CFR structure
Ubiquity	Handy access	Commercial Wi-Fi

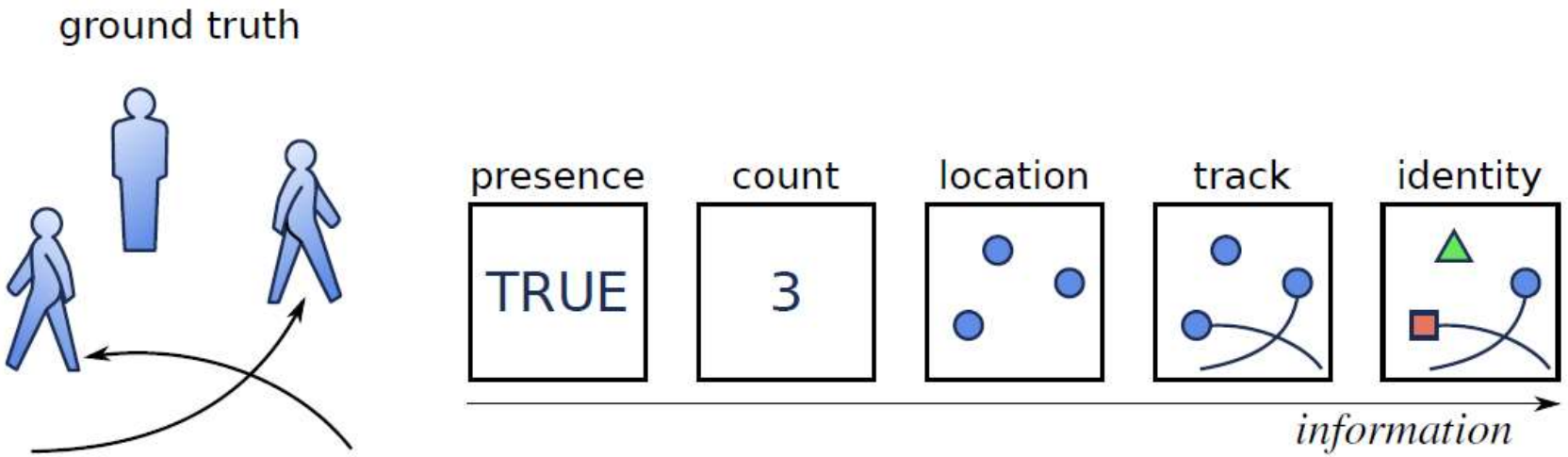
How **CSI** Benefits **WiFi Sensing**?

Outline

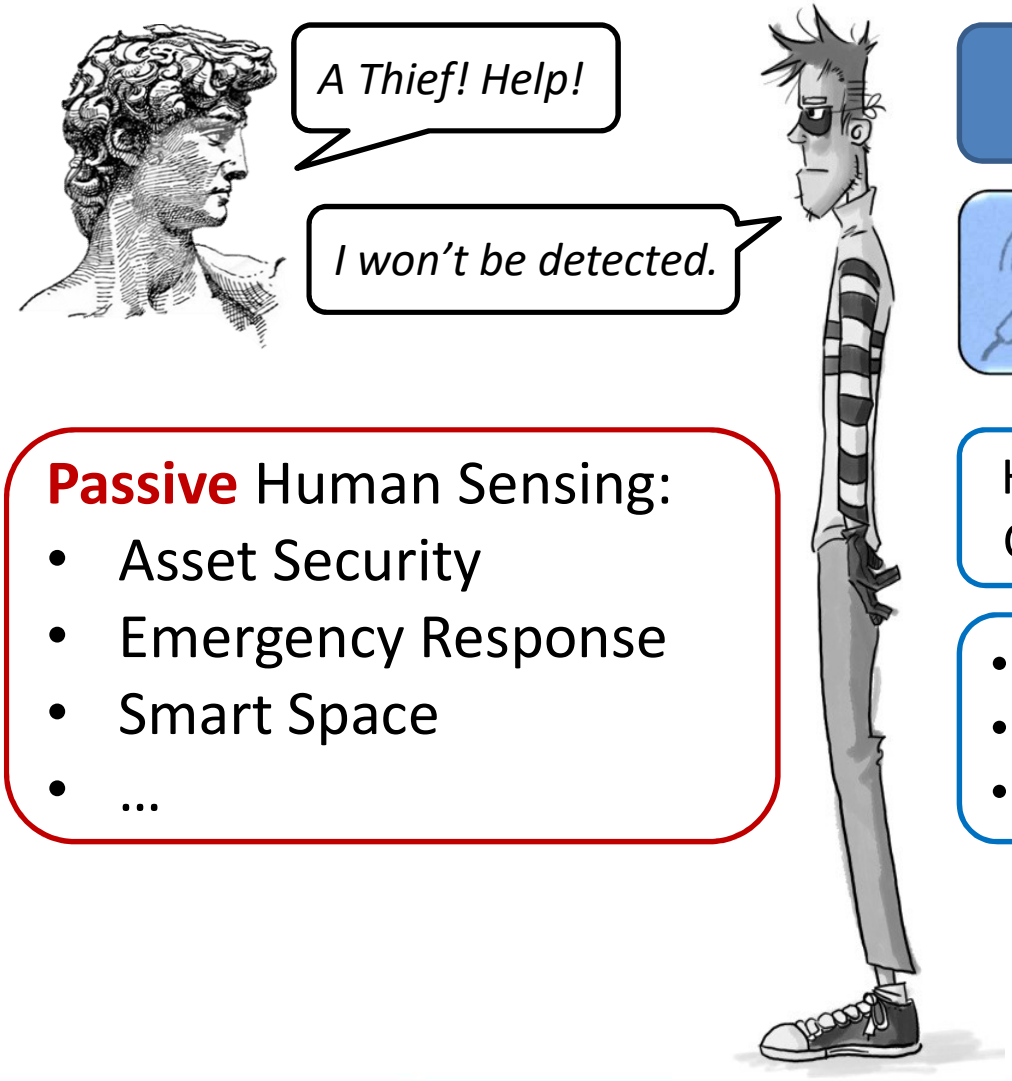
- Introduction
- Background
- **Method & Application**
  - **Sensing Coverage**
  - **Sensing Human with Dynamic Speeds**
  - **Sensing Static Human**
  - **Human Tracking**
  - **Human Interaction**
- Conclusion

Passive Human Sensing

- **Objective:**
  - Detect, Count, Localize, Track, Identify
- **Emerging Trend:**
  - Sense Humans **Passively**



Passive Human Sensing



Passive Human Sensing:

- Asset Security
- Emergency Response
- Smart Space
- …

Existing Methods

High Cost

LOS, Smoke, Directional

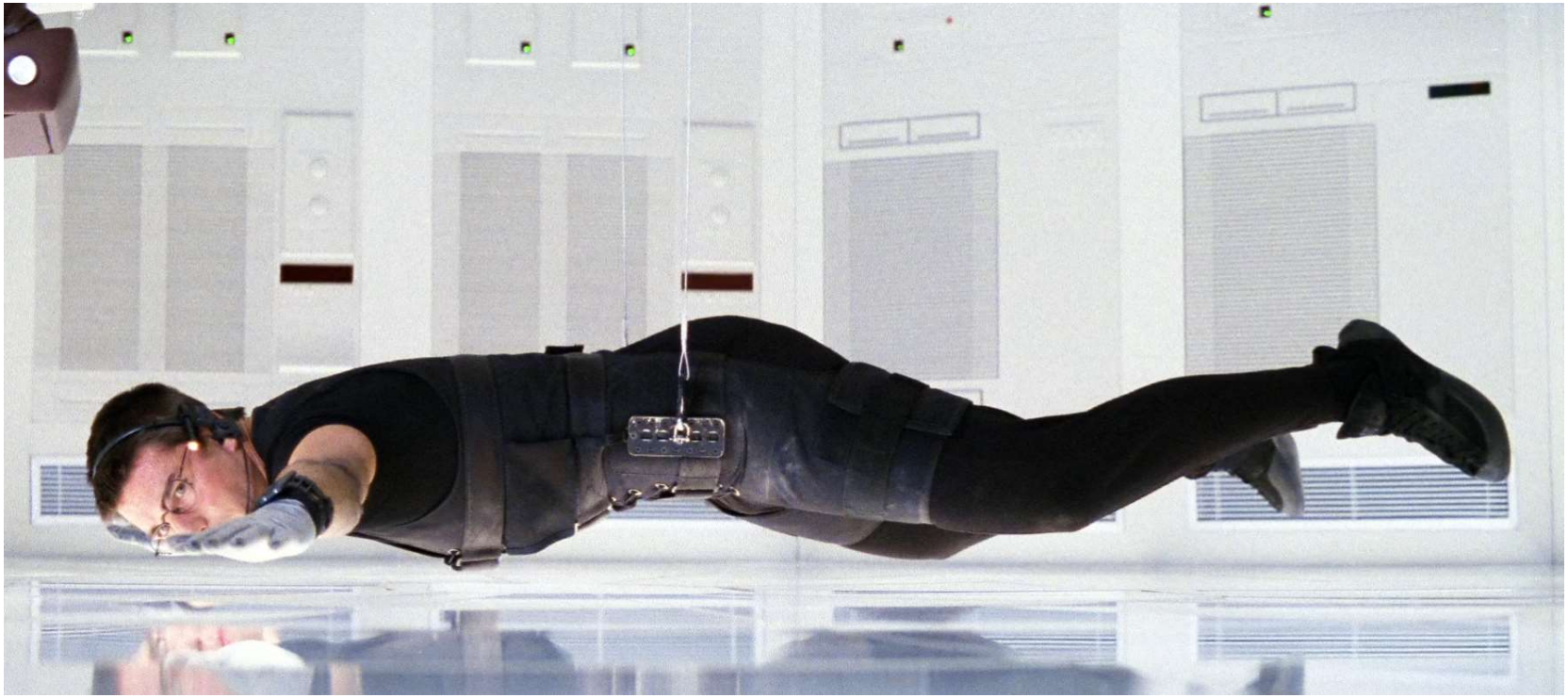
- Pervasive, low cost
- Penetrate walls and smoke
- No privacy issues

Limitation of Existing Methods

- Pressure Sensor

Limitation of Existing Methods

- Pressure Sensor



Limitation of Existing Methods

- Infrared Sensor

Limitation of Existing Methods

- Infrared Sensor

Limitation of Existing Methods

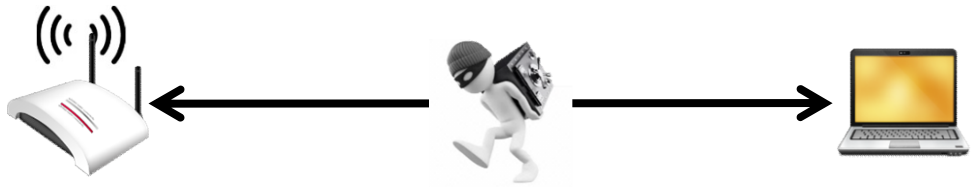
- Camera

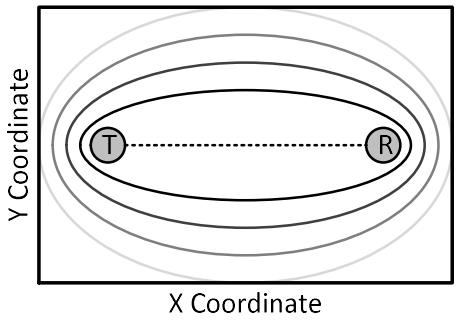
Limitation of Existing Methods

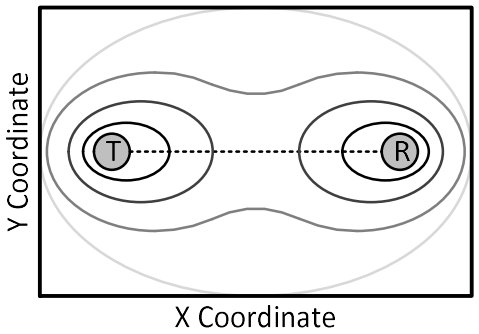
- Camera

Link-centric Coverage Shape

- Most monitoring units demonstrate a **link-centric** property
- **Disk-like** coverage is also desired in theory and application





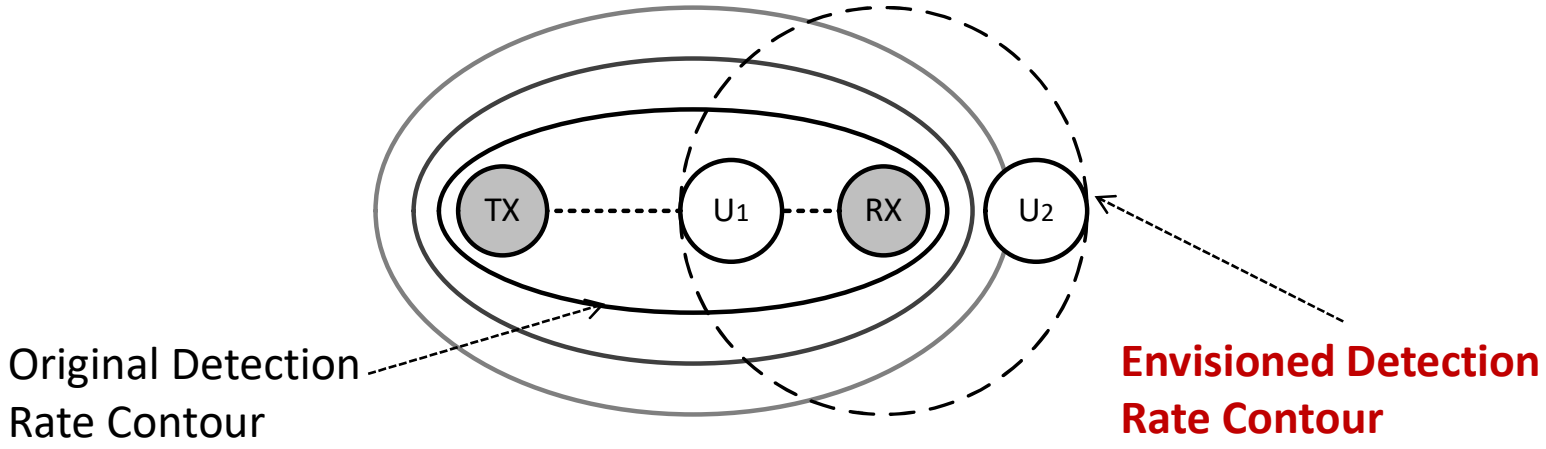


Scattering Dominant

Reflection Dominant

Omnidirectional Coverage?

- **Objective:**
  - Omnidirectional coverage under link-centric structure

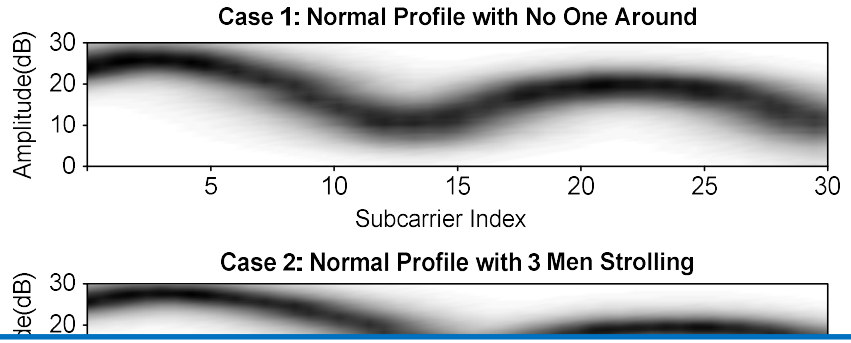


Insight: Exploit Multipath to **Blur** the Link-centric Coverage

Zhou et al, "Towards Omnidirectional Passive Human Detection ", IEEE INFOCOM, 2013

Fingerprinting Each Direction

- Requirements on the Fingerprints:
  - Sensitive to Human Presence **Nearby**
  - Resistant to Background Dynamics **Faraway**

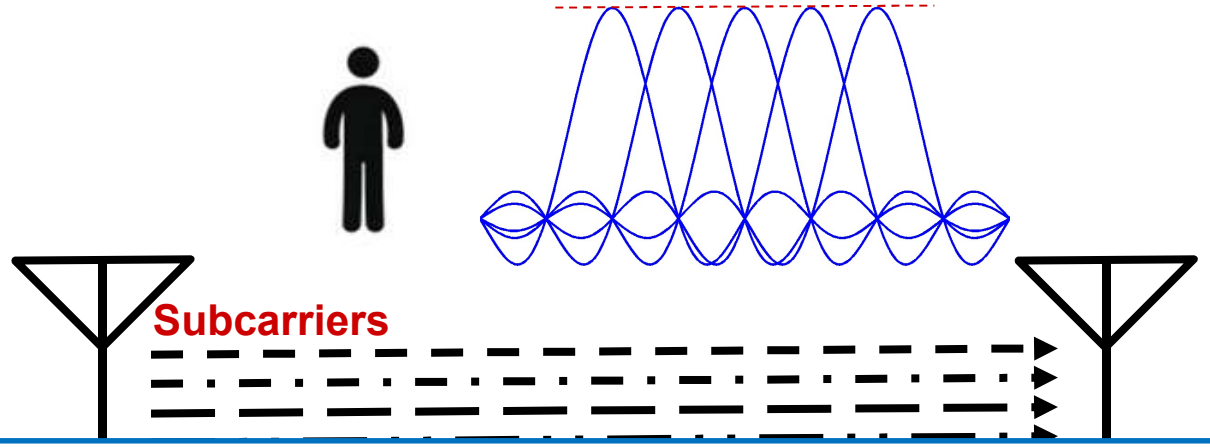


Stable under Dynamics **Faraway**

Disperse with **Nearby** Human Motions

Moving Target Detection

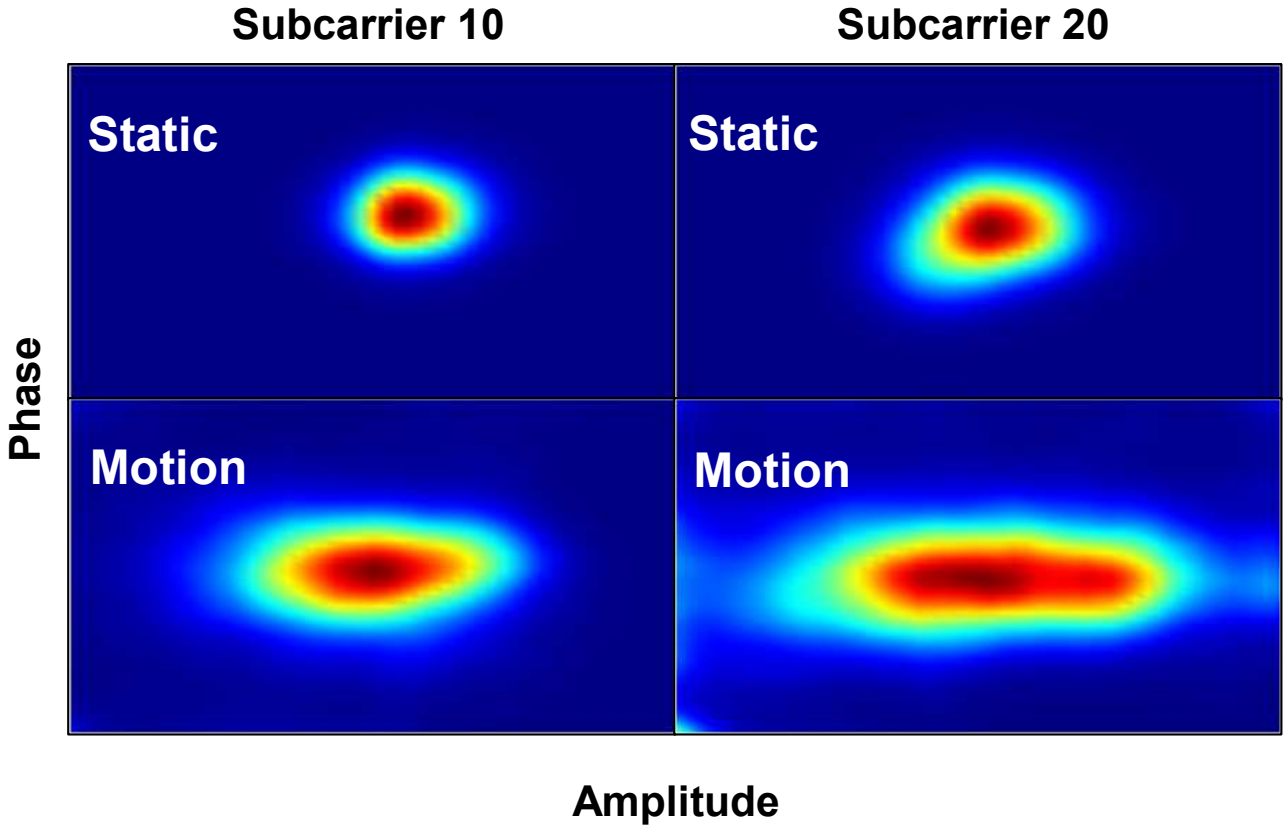
- **Observation:**
  - Signal variance reflects channel changes caused by motion



Slow Motions May be **Missed**
Due to **Low Sensitivity**

Coping with Dynamic Motion Speeds

- **Rationale:** motion brings about more dynamics in both amplitude and phase



"PADS: Passive Detection of Moving Targets with Dynamic Speed using PHY Layer Information", IEEE ICPADS.

Phase Sanitization

Raw CSI phase is useless because Tx/Rx are not synchronized, introducing a random phase shift.

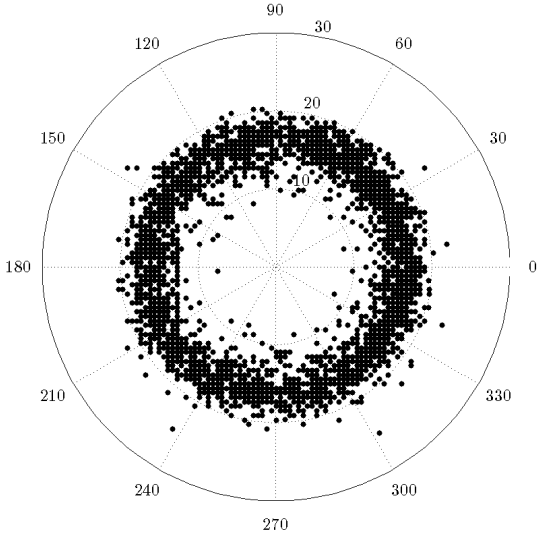
Measured Phase

$$\hat{\phi}_i = \phi_i - 2\pi \frac{k_i}{N} \delta + \beta + Z$$

Real Phase

Phase Shift

Phase relation for ith subcarrier



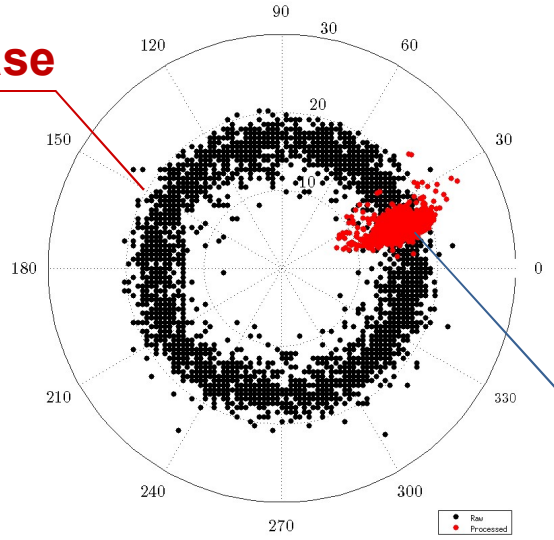
Raw phase distribution of ith subcarrier

Sanitization Result

- **Solution:** extract accurate phase-related information from raw CSI by dealing with asynchronous sender and receiver, asynchronous antennas, and noises.

$$\tilde{\phi}_i = \hat{\phi}_i - ak_i - b = \phi_i - \frac{\phi_n - \phi_1}{k_n - k_1} k_i - \frac{1}{n}\sum_{j=1}^{n} \phi_j$$

Raw Phase



Linear combination of real phases $\{\phi_i\}_{i=1}^{n}$

- Stable
- Sufficient to use

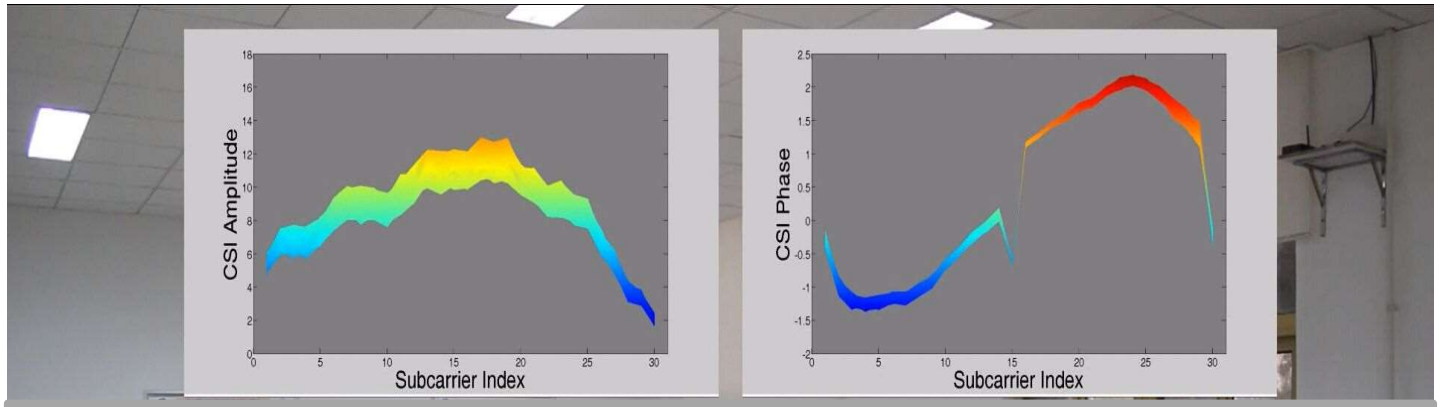
Sanitized Phase

Demo

优酷：http://v.youku.com/v_show/id_XODQ4MTY3MjY0.html

Youtube: http://youtu.be/As5JexOeOYY

Sensing Static Humans



Cannot Sense Static Humans

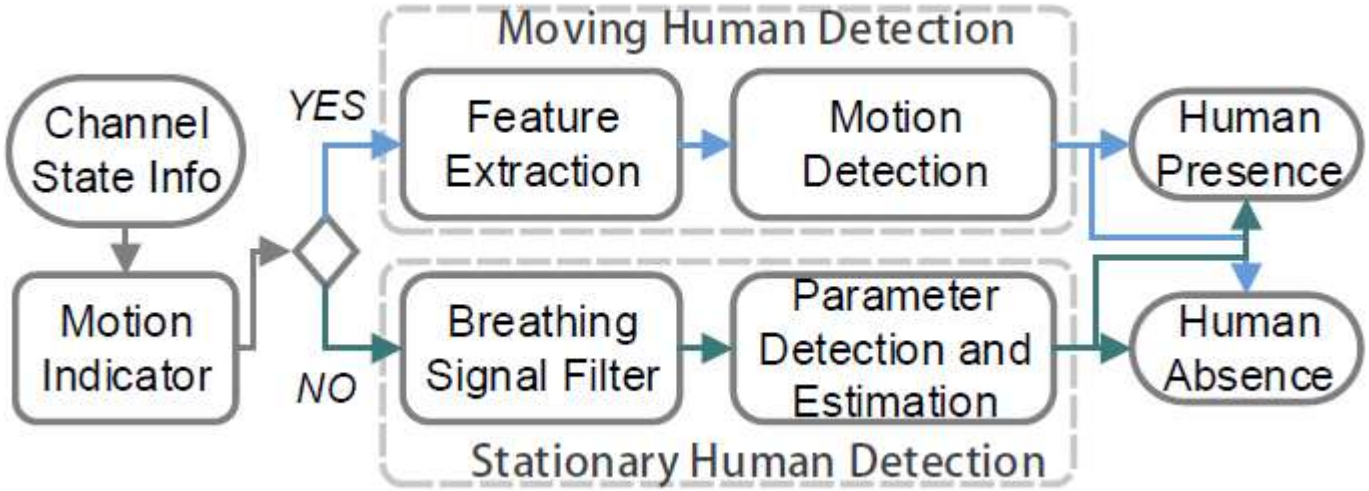
"Non-invasive Detection of Moving and Stationary Human with WiFi", IEEE JSAC.

Do not Move, Yet Breathe!

Breathing Induces **Rhythmic** Chest Motions!

- Opportunity to detect a static person
  - at least we breath periodically
  - breathing induced chest motion
- Goal
  - Detect Static Humans via Breathing-induced Signals
  - A Unified Scheme for Detection of Moving and Stationary Humans

Design & Challenges



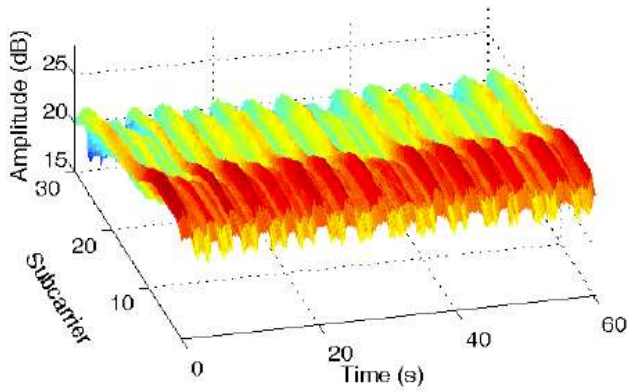
A unified framework for static & moving human detection (minute breathing-induced chest motion vs significant body motions)

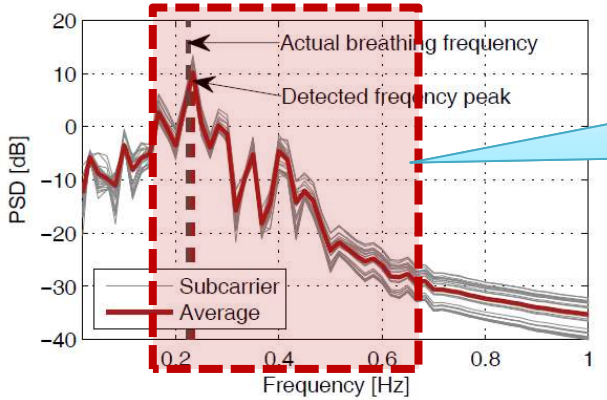
Identify weak human breathing patterns from wireless signals with environmental noises

Detect static humans without fingerprinting

Static Human Detection

Measurements

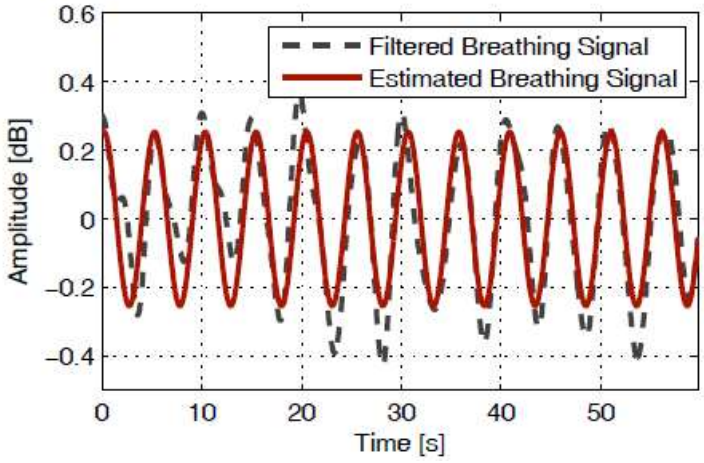




Breathing Freq.
[0.167, 0.667] *Hz*

Bandpass filter

Breath Estimate



$$H_k(i) = \bar{H}_k + G_k(i) + \epsilon_k(i),$$
$$G_k(i) = A_k \cos(2\pi f t_i + \phi_k),$$

Breathing Signals

$$RSS = \sum_{i=1}^{N} ||\hat{G}_k(i) - \tilde{H}_k(i)||^2$$

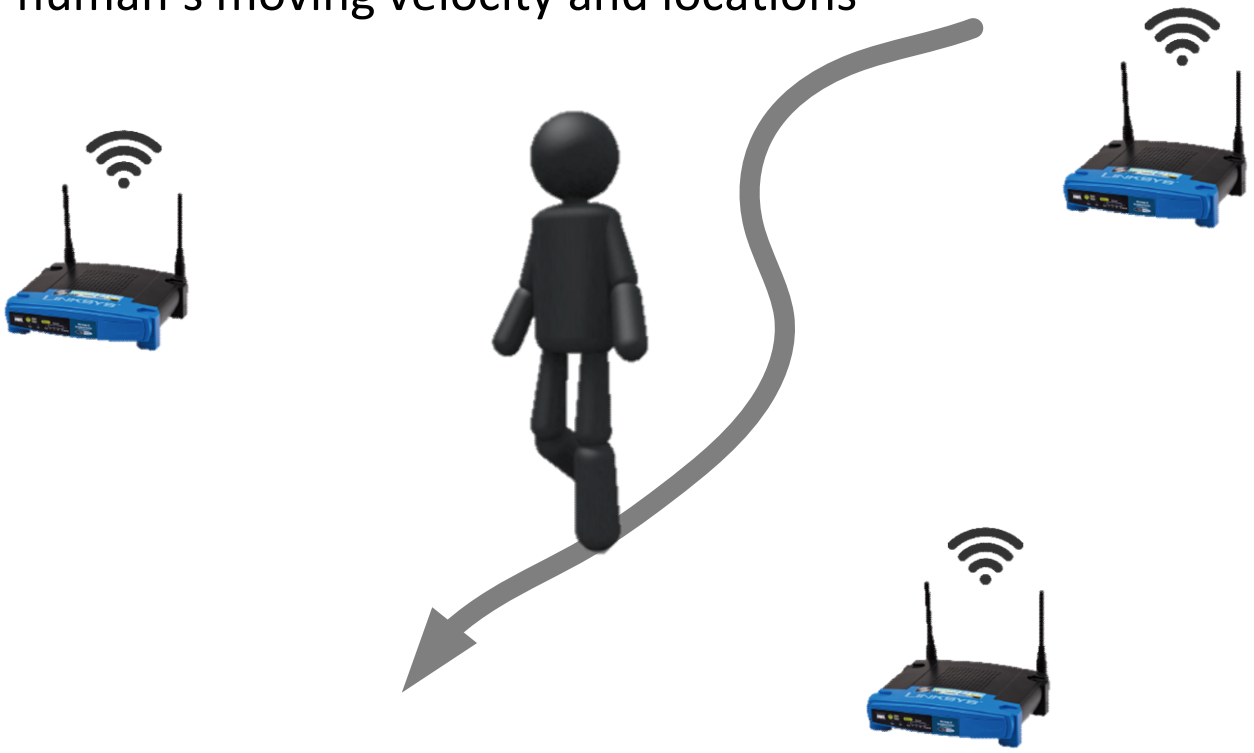
Residual sum of squares

$$\hat{f} = \frac{1}{\sum_{k=1}^{n} I(\hat{f}_k)} \sum_{k=1}^{n} \hat{f}_k I(\hat{f}_k)$$

Frequency diversity

Problem Statement

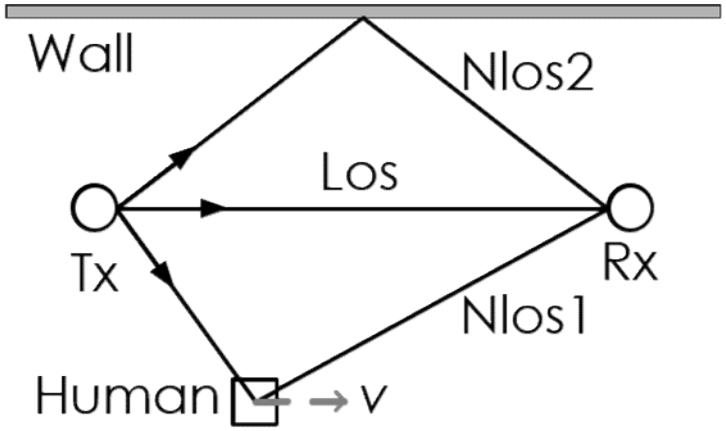
- Passive tracking with Wi-Fi
  - Key tech.: Using COTS Wi-Fi devices to simultaneously estimate human's moving velocity and locations



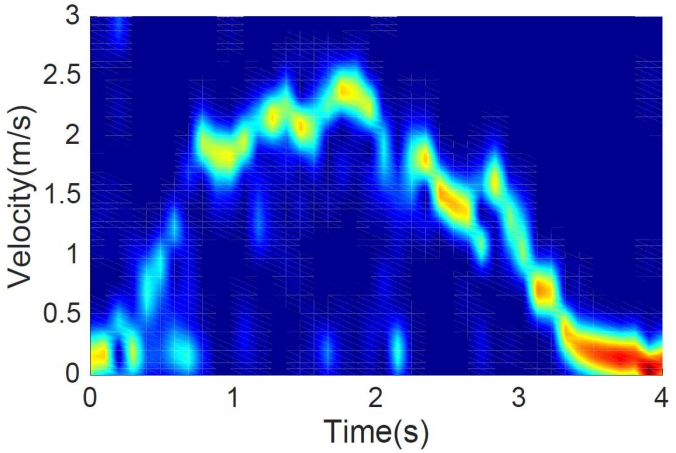
Kun Qian, et. al., "Decimeter Level Passive Tracking with WiFi", HotWireless 2016.

Preliminary

- CARM Models interaction between CSI and motion.



Walking Scenario



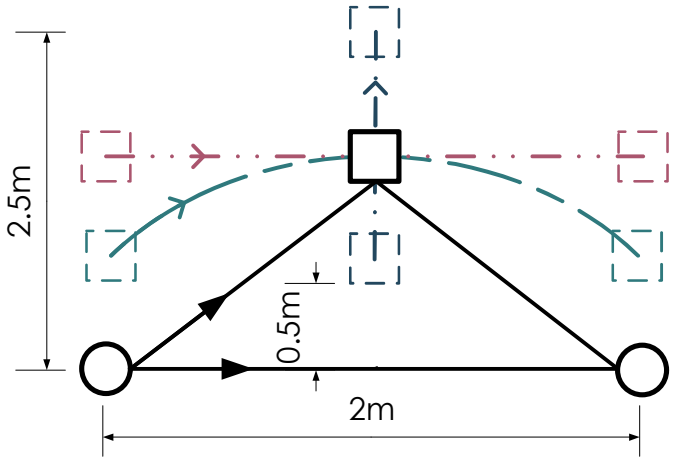
Spectrogram

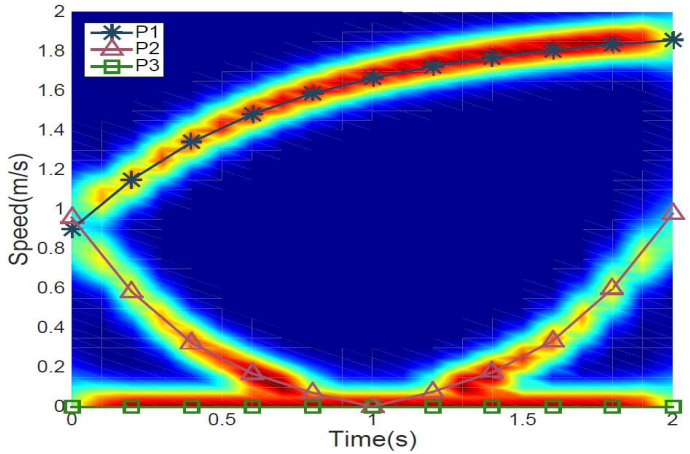
- CARM can extract the change rate of the length of the reflecting path

CARM, Mobicom '15

Challenge

- Path length change rate != real moving velocity (we want)
  - Path length change rate only reflects partial velocity.

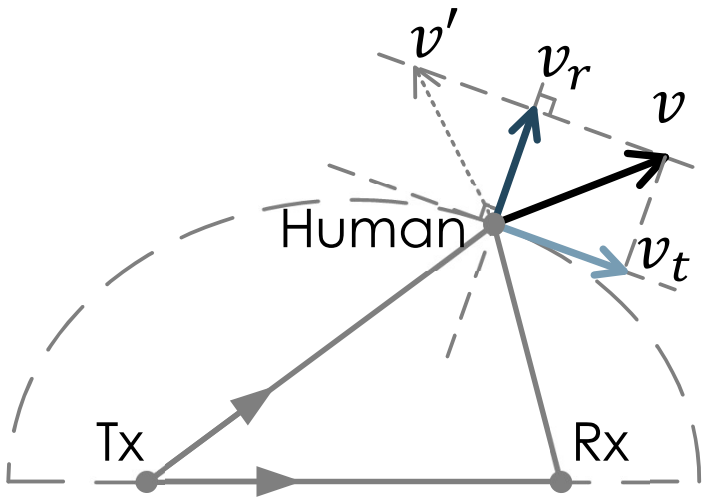




We introduce CSI-Mobility model.

The Single-Link Model

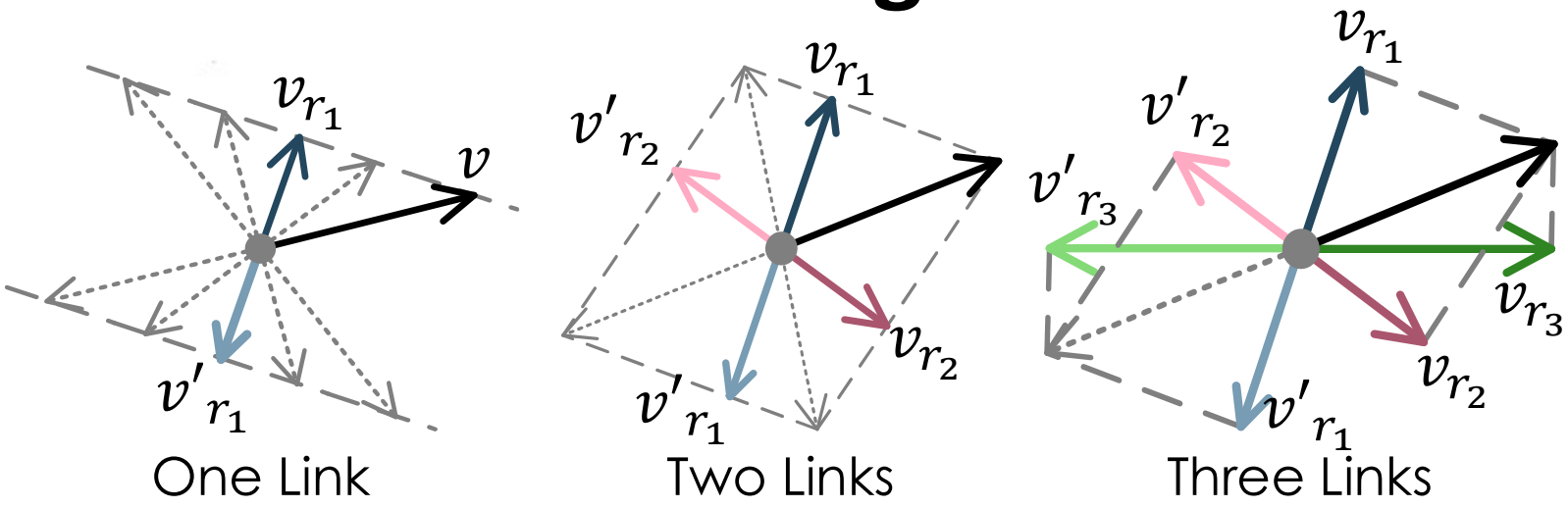
- From view of geometry,
  - Decompose: radial velocity v_r and tangential velocity v_t
  - v_r changes the path length and causes Doppler effect, while v_t not.
- From view of algebra,
  - Single link yields one equation.



Single-Link Model

Single Link is insufficient for tracking!

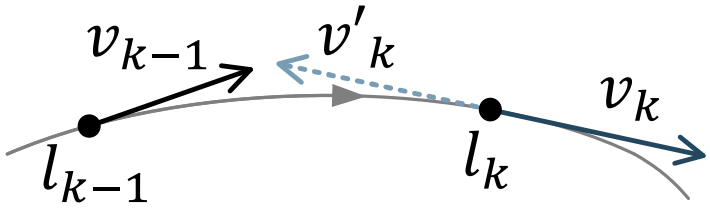
The Loss-of-Sign Model



One Link | Two Links | Three Links

- 2 links result in 4 candidates; 3 links result in 2 candidates
- Two ambiguous solutions always exist, no matter how many links are added.

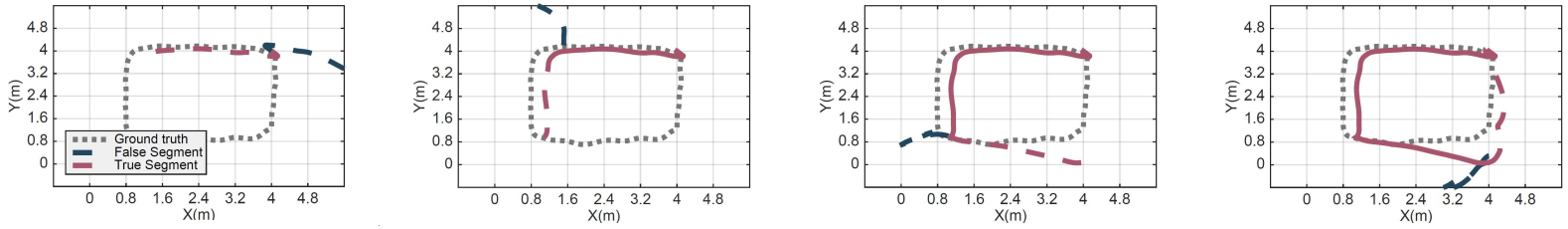
- We turn to leverage temporal dependency of human walking to figure out the only solution.



Resolve Ambiguity of Walking Direction

Implementation Issues

- Trace Refinement
  - Reinitialize tracking process at vulnerable moments.
    - The user takes a sharp turn.
    - The user walks slowly.



1st Segment 2nd Segment 3th Segment 4th Segment

  - Take extensive constraints within each segment.
    - Link-reflector distance.
    - Walking speed limits.
    - Turning angle.

Implementation Issues

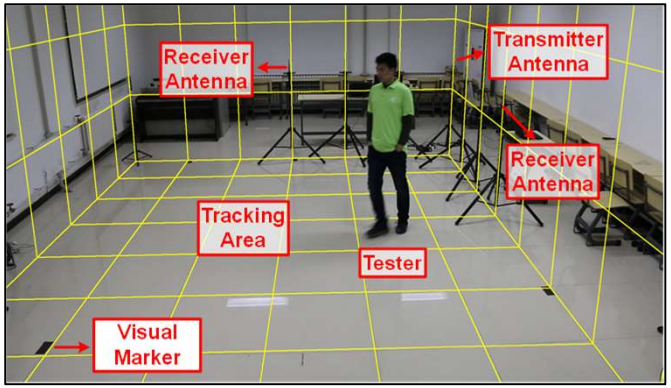
- Tracking Initialization
  - Treat overall trace T as a function of initial location l_0 and velocities of segments $v_{0,1}, \ldots, v_{0,m}$.

$$T_{\text{opt}} = T(\text{argmin}_{l_0, v_{0,1}, \ldots, v_{0,m}} \sum_{m=1}^{M} (\sum_{k=1}^{K_m} \text{err}_{\text{l},k} + \text{err}_{\text{v},k} + \lambda_m))$$

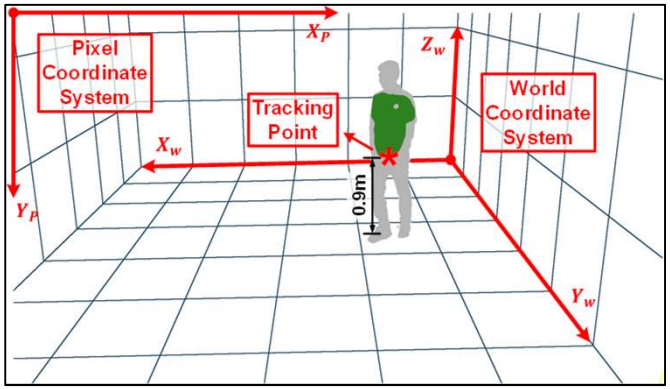
  - Error terms
    - err_{l} - Inconsistency between change rate of path length and solved velocity.
    - err_{v} - Deviation of current velocity against to last velocity estimation.
    - λ – Punishment from extensive constraints.

Experiment

- Devices
  - 1 transmitter, 2 receivers.
  - 6 links in total.
  - 5.825GHz channel.
  - 2000 pkts/s.
- Setup
  - Deployment schemes.
  - Trace shapes.
  - Volunteers.
- Ground truth
  - Video-based tracking

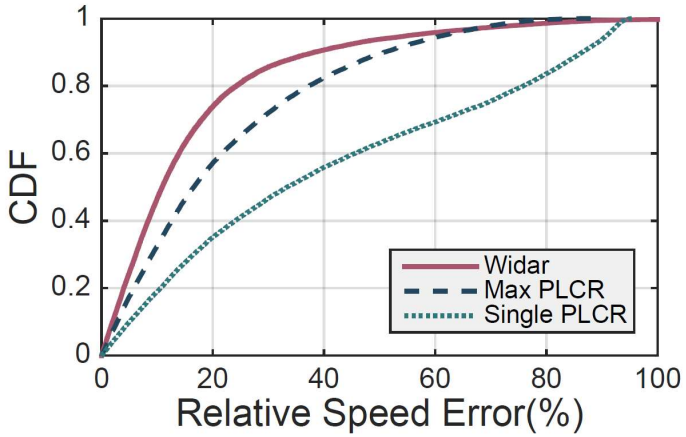


Experimental field

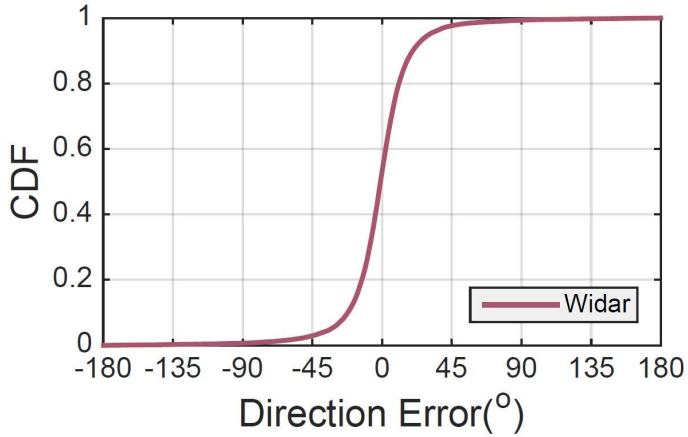


Coordinate transformation

Performance on Velocity



Velocity Magnitude

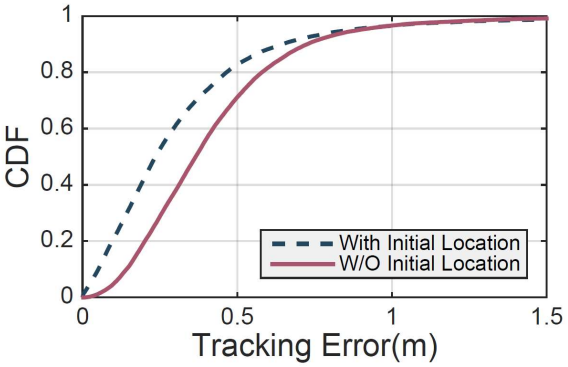


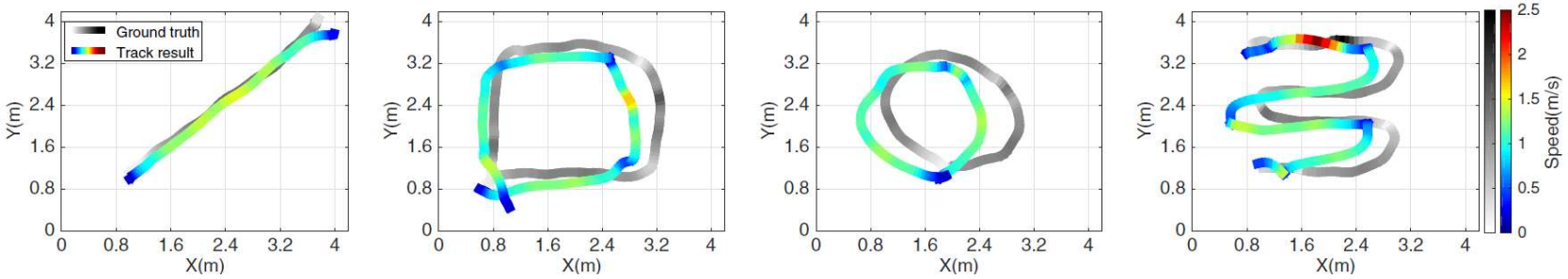
Velocity Direction

- *Widar* achieves the highest estimation accuracy, with a median error of 11%, for velocity magnitude.
- *Widar* achieves a 80-percentile error of 20° for velocity direction.

Performance on Location

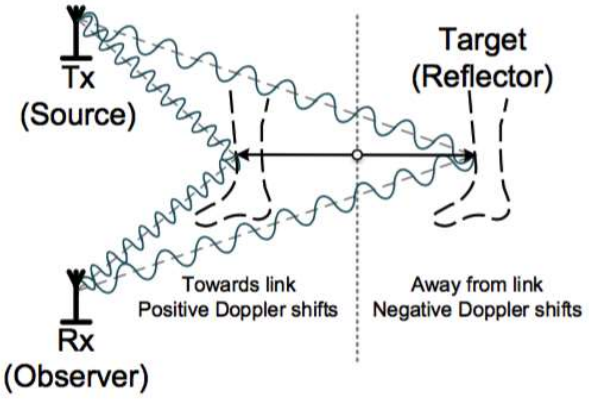
- *Widar* achieves a median tracking error of 24cm and 36cm, with and without initial location, and 90-percentile tracking error of 73cm.
- Decimeter Level Passive Tracking
- **Tracking examples**



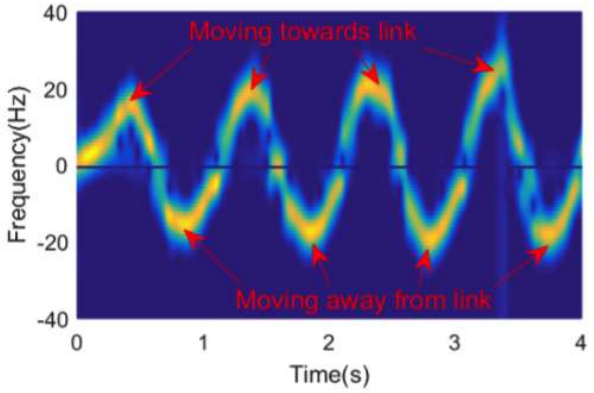


Doppler Effects

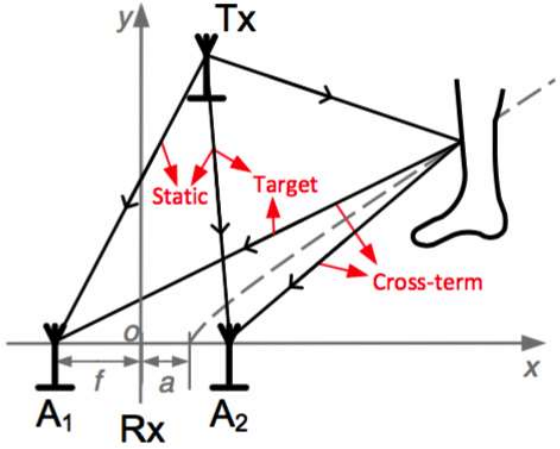
- Complete information of motion-induced Doppler shifts with only commodity Wi-Fi
- Harness antenna diversity to carefully eliminate random phase shifts while retaining relevant Doppler shifts
- We further correlate Doppler shifts with motion directions,



(a) Illustration of Doppler effect



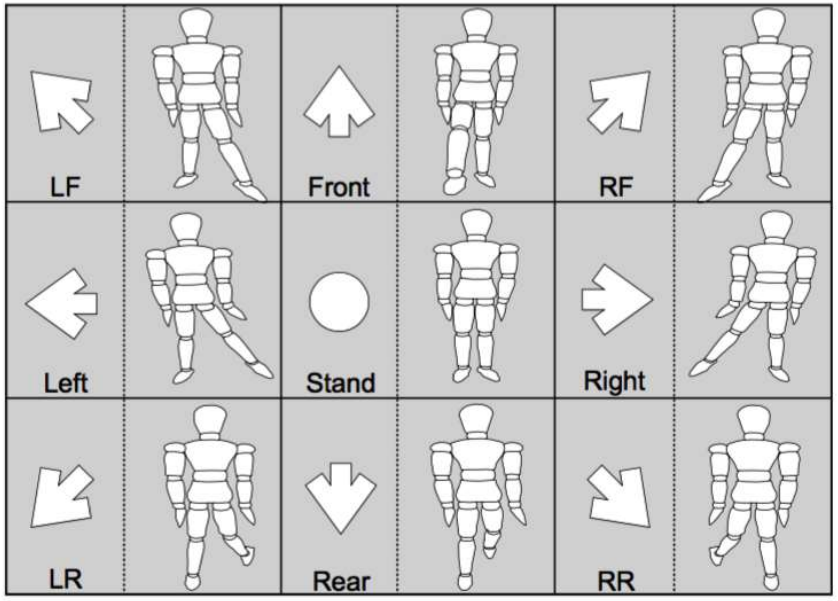
(b) Spectrogram of Doppler effect

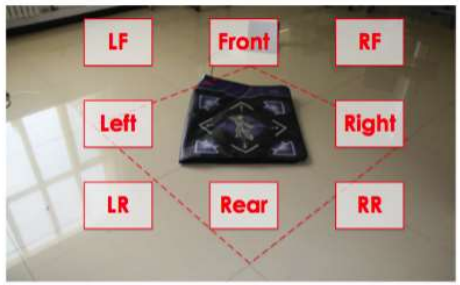


(c) Doppler effect with multiple antennas

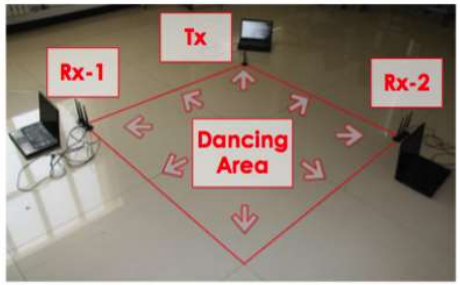
WiFi-based Dance Exergame

- Based on CSI-Mobility model, monitor motion and direction
- Design a Wi-Fi-based user interactive dance game
  - Previously, dance-pad is needed to record your action
  - Using WiFi instead of dance-pad to recognize behavior

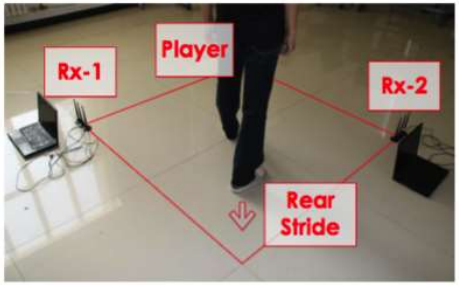




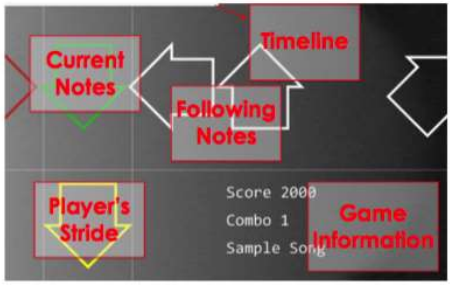
(a) Dancing mat



(b) *WiDance*



(a) User action

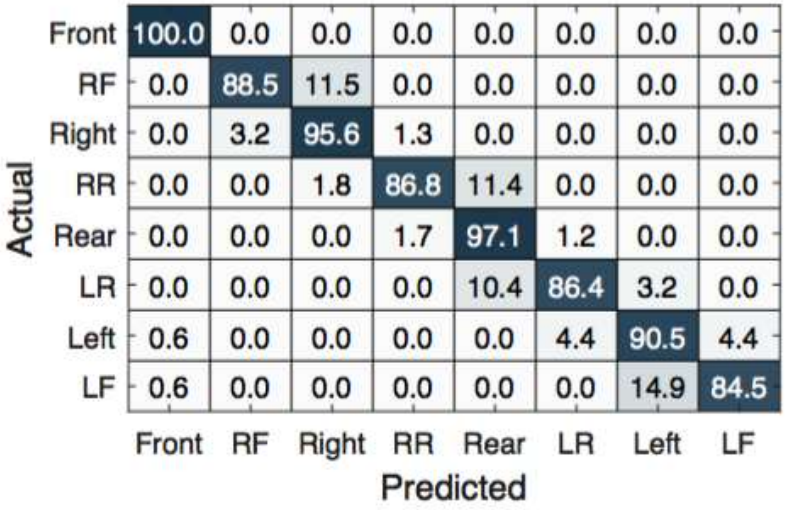


(b) Game GUI

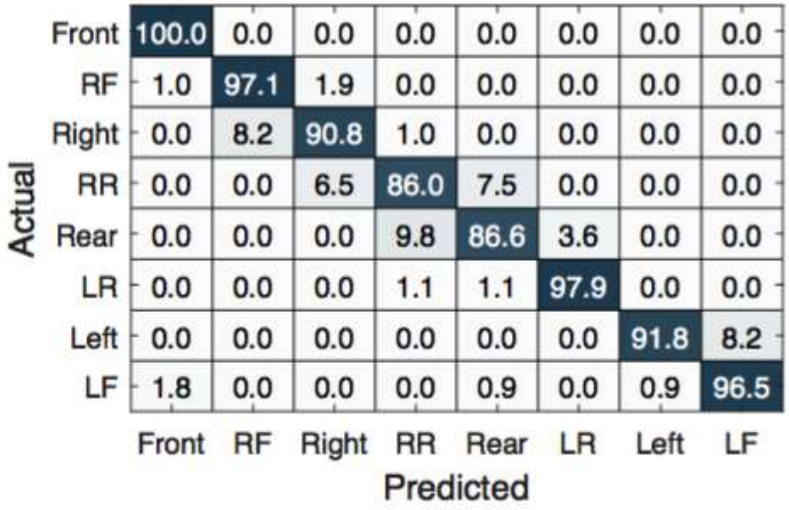
"Inferring Motion Direction using Commodity Wi-Fi for Interactive Exergames", ACM CHI 2017

WiDance

- 2 links woking on 5.825GHz, packet rate 1024Hz
- Overall accuracy of behavior recognition is 92% without learning, and 94% with HMM trained for 8 actions



(a) *WiDance* (overall 92%)



(b) HMM-*WiDance* (overall 94%)

Demo


Dancing in Wireless
A Ubiquitous Interactive Exergame with Wi-Fi

Outline

- Introduction
- Background
- Methods & Applications
- **Conclusion**

Future Direction

- **Training-free**
  - Environment-unrelated signal features
  - Learning algorithm
- **Killing application**
  - Security: Intruder detection
  - Robust performance for large deployment
- **Sensing multiple objects**

Summary

CSI, the fine-grained channel response accessible on commodity WiFi devices, acts as an essential upgrade of RSSI.

WiFi-Radar enables WiFi to sense wirelessly, sensorlessly, and contactlessly.

Due to its worldwide deployment, WiFi can be seen as the world's largest sensor network.

WiFi-Radar, together with emerging PHY layer information, initializes the pulse on next-generation mobile computing.

Look ahead

以前在电视剧中总能看到这样的场景，当几个人做坏事或者密谋做坏事的时候，一般会选择一个密室，关好门拉上窗帘，有经验的还会检查桌子下面是否有窃听器，完事后还要仪式性地念叨一句“天知地知，你知我知”。

今后，别忘了还要把**Wi-Fi** 关掉。

Reference

- Zheng Yang, et al., “From RSSI to CSI: Indoor Localization via Channel Response”, ACM Computing Surveys, Volume 46, No. 2, 2014.
- Zimu Zhou, et al., "Sensorless Sensing with WiFi", Tsinghua Science and Technology, Vol. 20, No. 1, pp. 1–6, 2015.
- Chenshu Wu, Zheng Yang, et al., "Non-invasive Detection of Moving and Stationary Human with WiFi", IEEE JSAC.
- Qian et al, “PADS: Passive Detection of Moving Targets with Dynamic Speed using PHY Layer Information”, IEEE ICPADS, 2014.
- Zimu Zhou, Zheng Yang, et al., “Omnidirectional Coverage for Device-free Passive Human Detection”, IEEE Transactions on Parallel and Distributed Systems (TPDS), Volume 25, Issue 7, Pages 1819 – 1829, July 2014.
- Kun Qian, et. al., “Inferring Motion Direction using Commodity Wi-Fi for Interactive Exergames”, ACM CHI 2017. (**Best Paper Honorable Mention Award**)
- Kun Qian, et. al., "Decimeter Level Passive Tracking with WiFi", HotWireless 2016.
- 杨铮、吴陈沭、刘云浩，《位置计算：无线网络定位与可定位性》，清华大学出版社，2014
- WiFi Radar Homepage：http://tns.thss.tsinghua.edu.cn/wifiradar/

WiFi雷达实验平台

- “WiFi雷达”实验平台包括微型工控机、TNS-CSI Tool、Visual CSI软件等，可实时显示无线信道状态信息（振幅与相位），并能同步存储观测数据，方便使用者观察和分析环境变化对信道状态的影响。
- WiFi雷达主页：http://tns.thss.tsinghua.edu.cn/wifiradar/

我的微信

我的微博

Thanks!

Q&A