Understanding and Modeling of WiFi Signal Based Human Activity Recognition

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Motivation

- WiFi signals are available almost everywhere and they are able to monitor surrounding activities.
WiFi signals are available almost everywhere and they are able to monitor surrounding activities.
Problem Statement

WiFi based Activity Recognition

- Using commercial WiFi devices to recognize human activities.

Advantages

✓ Work in dark
✓ Better coverage
✓ Less intrusive to user privacy
✓ No need to wear sensors
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Challenges

- Measurement from commercial devices are noisy and have unpredictable carrier frequency offsets.
- Needs robust and accurate models to extract useful information from measurements.
Key observations

- Multipaths contain both static component and dynamic component
- Each path has different phase
- Phases determine the amplitude of the combined signal
Understanding Multipath

- Motivation
- Modeling
- Design
- Experiments
- Conclusions

- Understanding Multipath

- Sender
- Receiver
- Wall
- Reflected by body
- Reflected by wall
- LoS path
- $d_k(0)$

- Combined Static Component
- Dynamic Component

- Q-axis
- I-axis
Understanding Multipath

Motivation Modeling Design Experiments Conclusions

Sender

Receiver

Wall

Reflected by

body

LoS path

d_k(t)

Reflected by

wall
Understanding Multipath

- Sender
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- LoS path

\[ d_k(t) \]

Combined

Dynamic Component

Static component
Interpreting CSI amplitude

- Phases of paths are determined by path length
- Path length change of one wavelength gives phase change of $2\pi$
- Frequency of amplitude change can be converted to movement speed
CSI-Speed Model

How accurate is it?

- Wave length $\rightarrow 5 \sim 6\, cm$ in 5 GHz band

Waveform with regular moving speed

CSI amplitude changes are close to sinusoids
How accurate is it?

- Wave length $\rightarrow 5 \sim 6\text{cm}$ in 5 GHz band

CSI amplitude changes are close to sinusoids

Average distance measurement error of 2.86 cm
CSI-Speed Model

How robust is it?

- Robust over different multipath conditions and movement directions
- Linear combination of multipath do not change frequency

Speed distribution of different activities in different environments
CSI-Activity Model

Activities are characterized by

- Movement speeds
- Change in movement speeds
- Speeds of different body components

Walking

Falling

Sitting down
CSI-Activity Model

- Use time-frequency analysis to extract features
- Use HMM to characterize the state transitions of movements

Walking

Falling

Sitting down
CSI-Activity Model

- Build one HMM model for each activity
- Determine states based on observations in waveform patterns
- State durations and relationships are captured by transition probabilities
CSI measurement collection

Noise reduction

Activity data collection

Activity detection and segmenting

Feature extraction

HMM based activity recognition

Monitoring records

Online monitoring

Model generation

HMM training

HMM Model

Activity data collection

Model generation

HMM training

HMM Model
Data Collection

Motivation  Modeling  Design  Experiments  Conclusions

$N \times M \times 30$ CSI streams

30 subcarriers

Time (seconds)

11 11.5 12 12.5

60 65 70 75

CSI
Noise Reduction

Correlation of CSI on different subcarriers

- Subcarriers only differ slightly in wavelength
- Subcarriers have the same set of paths, with different phases

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wave length</th>
</tr>
</thead>
<tbody>
<tr>
<td>312.5kHz</td>
<td>5.150214 cm</td>
</tr>
<tr>
<td></td>
<td>5.149662 cm</td>
</tr>
</tbody>
</table>
Correlation in CSI Streams

Phase changes by $2\pi$

Noises present in all streams
Noise Reduction

Combines $N \times M \times 30$ subcarriers using PCA to detect time-varying correlations in signal.
Real-time Recognition

- Activity detection
  - Use both the signal variance and correlation to detect presence of activities

- Feature extraction
  - Time-frequency analysis (DWT)

- HMM model building
  - Eight activities
    - Walking, running, falling, brushing teeth, sitting down, opening refrigerator, pushing, boxing
  - More than 1,400 samples from 25 persons as the training set
Evaluation Setup

- Commercial hardware with no modification
  - Transmitter: NetGEAR JR6100 Wireless Router
  - Receiver: Thinkpad X200 with Intel 5300 NIC

- A single communicating pair is enough to monitor 450 $m^2$ open area

- Measurement on UDP packets sent between the pair

- Sampling rate 2,500 samples per second
## Evaluation Results

<table>
<thead>
<tr>
<th>True activity</th>
<th>R</th>
<th>W</th>
<th>S</th>
<th>O</th>
<th>F</th>
<th>B</th>
<th>P</th>
<th>T</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Walking</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Sitting</td>
<td>0.000</td>
<td>0.000</td>
<td>0.947</td>
<td>0.030</td>
<td>0.011</td>
<td>0.000</td>
<td>0.012</td>
<td>0.000</td>
<td>0.000</td>
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<tr>
<td>Opening</td>
<td>0.000</td>
<td>0.005</td>
<td>0.150</td>
<td>0.803</td>
<td>0.042</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Falling</td>
<td>0.000</td>
<td>0.010</td>
<td>0.041</td>
<td>0.010</td>
<td>0.939</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<tr>
<td>Boxing</td>
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<td>1.000</td>
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<td>0.000</td>
</tr>
<tr>
<td>Pushing</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Brushing</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<td>0.000</td>
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<tr>
<td>Empty</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

- Ten-fold validation accuracy: **96.5%**
- Detects human movements at **14** meters
- Real-time recognition on laptops
- Packet sending rate can be as low as 800 frames per second
• Models are robust to environment changes

• **Train once**, apply to different scenarios

• Training use database collected in lab with different users

• Test in with users **not** in the training set
  - Open lobby
  - Apartment (**NLOS**)  
  - Small office

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Evaluation on Robustness

- **Training location**
  - Lab
  - Walking/running route
  - Table
  - Fridge

- **Testing location**
  - Apartment
  - Table
  - Fridge
  - Kitchen
  - Bathroom
Evaluation on Robustness

- Consistent performance in unknown environments, with more than 80% average accuracy

<table>
<thead>
<tr>
<th>Environments</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>lab</td>
<td>0.5</td>
</tr>
<tr>
<td>lobby</td>
<td>0.7</td>
</tr>
<tr>
<td>apartment</td>
<td>0.8</td>
</tr>
<tr>
<td>office</td>
<td>0.9</td>
</tr>
</tbody>
</table>

![Bar chart showing accuracy across different environments]
Conclusions

- CSI measurements contain fine-grained movement informations

- CSI-Speed model
  quantifies the correlation between CSI value dynamics and human movement speeds

- CSI-Activity model
  quantifies the correlation between the movement speeds of different human body parts and a specific human activity

- Our models are robust to environment changes
Thank you!

Questions?