Human Detection and Object Categorization

Using Wi-Fi Channel State Information

From changes in radio propagation to decisions about people, motion, and materials.

Motion and activity

CARM · Wi-MoID

Data and material cues

FuseFi · WiMi

First, separate the sensing tasks

Task	Question	Example
Motion detection	Did something move?	Activity onset in CARM
Source discrimination	Was it a person or another moving source?	Wi-MoID
Activity recognition	What is the person doing?	CARM; FuseFi HAR
Material identification	What material is in the sensing path?	WiMi

Human detection needs evidence about the moving source. Object identity and material require separate labels.

Why movement changes a Wi-Fi signal

Transmitter → Room and target → Receiver

- The receiver gets a direct signal plus reflected copies.
- A moving body changes reflected path lengths and phases.
- Those copies add or cancel, so measured amplitude changes too.

Wi-Fi sensing links measured channel changes to possible causes in the scene.

What is Channel State Information?

$$y_{k(t)} = H_{k(t)} x_{k(t)} + n_{k(t)}$$

A measurement of the radio path

- x_k: known transmitted signal.
- y_k: received signal; n_k: noise.
- H_k: complex gain on subcarrier k.

More detail than one signal-strength number

- Amplitude and phase across subcarriers and antenna pairs.
- A sequence of packets gives changes over time.
- Access needs supported hardware and a CSI extraction tool.

CARM: connect channel changes to motion

$$H(t) = H_{\text{static}} + ae^{-j2\pi\frac{d(t)}{\lambda}}$$

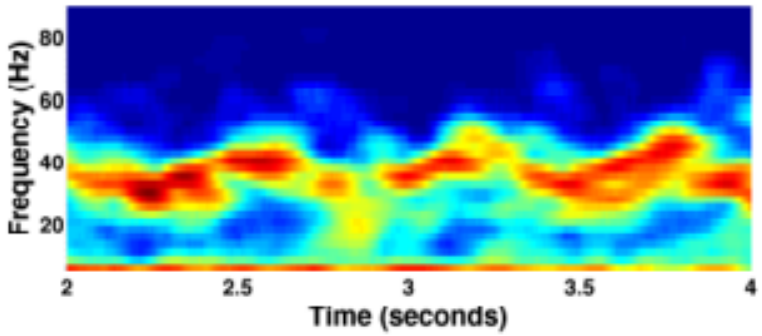
$$f_{\text{motion}} = \frac{\left|\frac{\mathrm{d}d(t)}{\mathrm{d}t}\right|}{\lambda}$$

H_{static}: static paths; a: reflection gain; $d(t)$: path length; λ: wavelength.

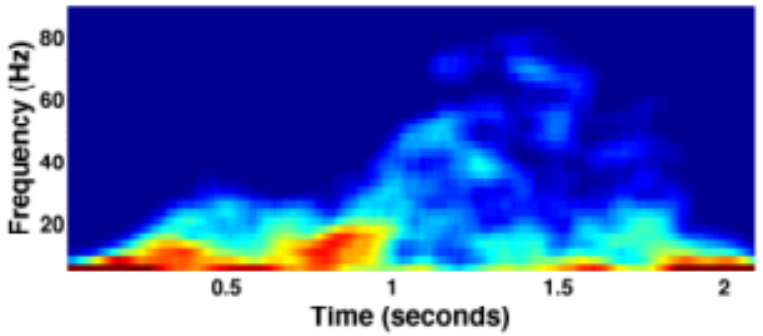
- A changing path length $d(t)$ rotates the reflected signal's phase.
- Its interference with static paths creates changes in CSI power.
- Frequency gives a **path-length rate**. Body-speed estimates also need geometry.

Motion-related frequency patterns provide physically motivated activity features.

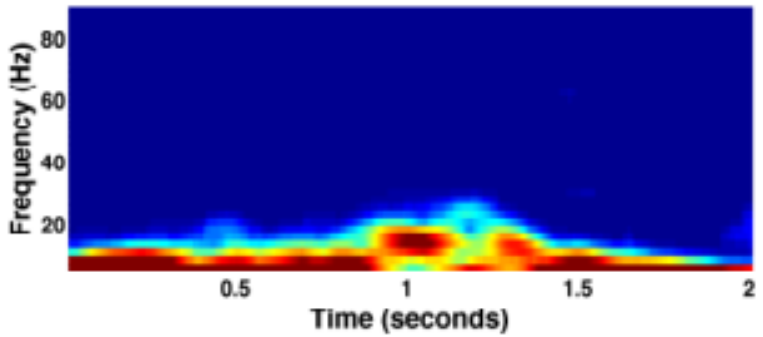
Reading a motion signature



(d) Sepctrogram for walking



(e) Sepctrogram for falling



(f) Sepctrogram for sitting down

Walking

A sustained band of motion-related energy.

Falling

A brief rise toward higher frequencies.

Sitting down

Lower-frequency motion than the fall example.

CARM: turn motion into an activity sequence

CSI streams → PCA denoising → Wavelet features → Activity HMMs

- **PCA:** combine correlated subcarrier streams; reduce device noise.
- **Wavelets:** track energy in different motion-speed ranges over time.
- **Hidden Markov models:** match sequences of movement states.

A fall has a sequence of speed changes and movement states.

CARM: read the result with its protocol

Evaluation	Accuracy	Context
Lab cross-validation	96.5%	10 folds; 2,500 CSI samples/s
Separate lab / lobby tests	90% / 93%	Two users outside training
Separate office / apartment tests	83% / 80%	Different rooms and feasible activity sets

- Training data: 25 volunteers; eight activities plus no activity.
- One active mover is the supported case; simultaneous movers remain a limit.

Wi-MoID: identify the moving source

Human

Bipedal motion and changing stride speed.

Pet

Quadrupedal motion; gait and small movements.

Cleaning robot

Wheel-driven motion with a different speed pattern.

- First detect a motion segment, then classify its source.
- Combine gait evidence with speed and signal statistics.
- Test behavior changes such as stops, turns, and small movements.

Wi-MoID: physical features support edge inference

CSI autocorrelation → 11 features → SVM → Temporal refinement

- **Autocorrelation:** compare the signal with a delayed copy.
- Model its shape to estimate speed; extract stride and statistical features.
- An HMM refines labels across movement segments.

Physical structure reduces a long CSI recording to a small classifier input.

Wi-MoID: check building transfer and edge cost

Author-demo setting	Accuracy	False alarm
Validation: two training/validation environments	97.34%	1.75%
Testing: three unseen environments	95.98%	1.99%

- PICO-IMX7 edge demo: 38% CPU and 0.87 MB memory.
- Aggregate scores leave per-class and all-day alarm behavior unresolved.

FuseFi: ordinary traffic has irregular timing

Controlled sensing packets

Regular timing and a fixed format.

Extra probes consume communication airtime.

Ordinary communication

Gaps, bursts, changing power, and packet formats.

Different observations arrive on each band.

- Use data, management, and control packets together.
- Keep timestamps to represent elapsed time between observations.

FuseFi: learn from values and observation times

CSI + time + metadata → Sanitize → Time-aware attention → GRU + classifier

- Group packet formats, normalize amplitudes, align compatible groups, and thin bursts.
- Attention uses CSI content and continuous timestamps.
- Fixed reference times produce a fixed-length **latent** sequence.

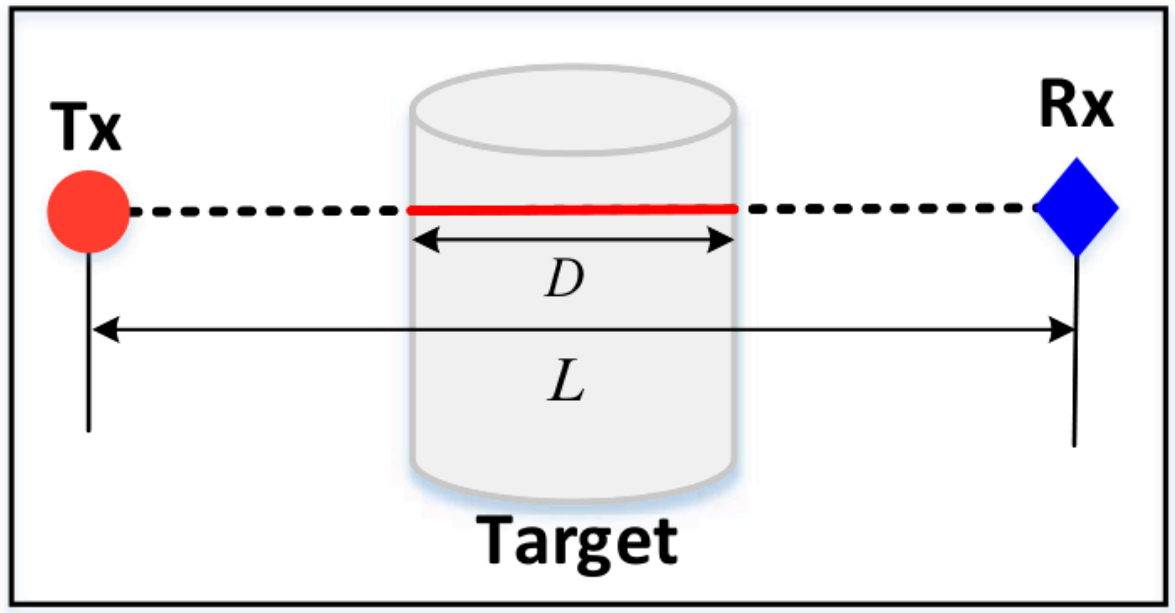
Attention combines amplitude observations from both bands into a learned representation.

FuseFi: richer data helps; new users are harder

Setting	Accuracy	Protocol
All 5 GHz frames	94.31%	Subject-mixed segments
All frames, both bands	96.88%	Subject-mixed segments
Leave one subject out	41.6%	No labeled user calibration

- CommCSI-HAR: eight people, six activities, one office.
- Raspberry Pi 5: 8.65 ms **neural inference**; sanitization remains offline.

WiMi: identify what the signal passes through



A different sensing geometry

- Put the target on the direct transmitter-receiver path.
- Measure an empty-container baseline, then settled liquid.
- Material changes attenuation and phase during penetration.

WiMi: remove thickness before classification

Baseline + target → Calibrate CSI → Material feature → SVM label

- Inter-antenna differences reduce shared clock and phase errors.
- Denoising and stable subcarriers improve amplitude and phase.
- Log attenuation and phase shift share a traversal-length factor.

Combine the two measurements to cancel thickness in the model. Then classify known materials.

WiMi: evaluate the known-material decision

Reported lab accuracy

96%

Ten liquid labels.

Read the conditions

- Twenty collection repetitions per target.
- No train/test split is specified.
- Static liquid; one target on the direct link.
- Metal or foil containers block the required penetration.

Two objects can share a material and have different purposes. Material and object category need separate labels.

Four papers, four different contributions

System	Useful signal	What it contributes
CARM	Motion-frequency sequences	Physical model and activity recognition
Wi-MoID	Human/nonhuman motion structure	Discrimination of moving sources
FuseFi	Irregular multi-band CSI	Learning from ordinary traffic
WiMi	Penetration phase and attenuation	Known-material classification

Limitations of the current evidence

System	Limit to carry into deployment
CARM	One active mover; geometry affects motion features.
Wi-MoID	Moving-source labels; stationary people and all-day alarm behavior need tests.
FuseFi	New-user transfer is weak; sparse traffic and offline sanitization limit deployment.
WiMi	Settled liquid on the direct link; baseline needed; train/test split unspecified.

Remaining research challenges

Separate the causes

- Distinguish target cues from room, path, and device effects.
- Separate several moving sources.
- Handle weak motion and sparse observations.

Make decisions reliable

- Transfer to new users, rooms, and objects.
- Reject unknown classes; expose uncertainty.
- Measure false alarms, misses, and full-system cost.

Future directions and possible uses

Possible use	Research direction	Required validation
Home alarms	Adapt to new rooms; reject unknown motion	Alarms per day with pets and devices
Activity-change alerts	Long-term temporal models	Missed events and human review
Room automation	Combine multi-link motion and presence cues	Stationary occupants; privacy controls
Material checks	Calibrated holders and richer phase features	New containers, mixtures, and held-out trials

What should we take away?

- **Start with the mechanism:** movement changes multipath; materials alter transmission.
- **Choose the task:** detecting motion, recognizing an activity, and identifying a material are different goals.
- **Read the test protocol:** new-user and new-room tests measure transfer.

CSI is a useful source of evidence. General human detection and object categorization still need explicit tests against alternative causes.