Privacy-Preserving Indoor Human Activity Sensing Using Acoustic Micro-Doppler

(A Physics-Based Acoustic Sensing System for Human Presence Detection)

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ABSTRACT

This project presents a privacy-preserving indoor human activity sensing system based on acoustic micro-Doppler. An ultrasonic tone near 18 kHz is transmitted into an indoor environment and its reflections are recorded using a standard microphone. Human motion introduces Doppler frequency shifts that are extracted using spectrogram analysis and converted into physics-based features. A machine learning classifier then distinguishes between empty and occupied conditions. Because the system uses only frequency shifts around an ultrasonic carrier and does not process audible audio, it preserves privacy while enabling reliable human presence detection.

➢ INTRODUCTION

Traditional indoor sensing systems rely on cameras or microphones, which capture visual appearance, speech, and identity. While effective, these systems raise serious privacy concerns. A privacy-preserving alternative is to sense humans using physical motion signatures rather than semantic content.

This project presents a low-cost sensing system that detects human presence and motion inside a room using ultrasonic acoustic micro-Doppler. An ultrasonic tone near 18 kHz is transmitted into the room, and the reflected signal is recorded. When a human moves, their body causes frequency shifts in the reflected wave. These Doppler shifts are extracted and used as machine-learning features to classify whether a human is present.

Because the system only analyzes frequency changes and never records intelligible audio, it preserves privacy while still enabling robust sensing.

➢ PHYSICS OF ACOUSTIC DOPPLER

When a wave reflects from a moving object, its frequency changes. This phenomenon is called the **Doppler effect**.
For sound waves, the Doppler shift is given by:

$$\Delta f = \frac{2v}{c} f_0$$

where
v = velocity of the moving object
c = speed of sound (≈ 343 m/s)
f_0 = transmitted frequency

The factor of 2 appears because the wave travels to the target and back.

In this project:

- The transmitted frequency is around 18 kHz
- Human body parts (arms, torso, legs) move at velocities between 0.1–2 m/s

This produces Doppler shifts in the range of a few to tens of Hz, which appear as **micro-Doppler patterns** in the spectrogram.

These micro-Doppler signatures encode:

- Motion speed
- Motion rhythm
- Presence vs absence of movement

They do not encode speech or identity.

➢ SYSTEM DESIGN

The proposed system follows a physics-driven acoustic sensing pipeline:

- A continuous 18 kHz ultrasonic tone is transmitted using a laptop speaker.
- The sound reflects from the indoor environment and any moving human body.
- A microphone records the reflected waveform.
- A time–frequency spectrogram is computed from the recorded signal.
- The narrow band around 18 kHz is isolated to remove audible noise.
- Static reflections (walls and furniture) are removed by mean subtraction.
- The remaining signal contains only motion-induced Doppler components.
- Physics-based features are extracted from this Doppler representation.
- A machine learning classifier predicts human presence from these features.

➢ EXPERIMENTAL SETUP

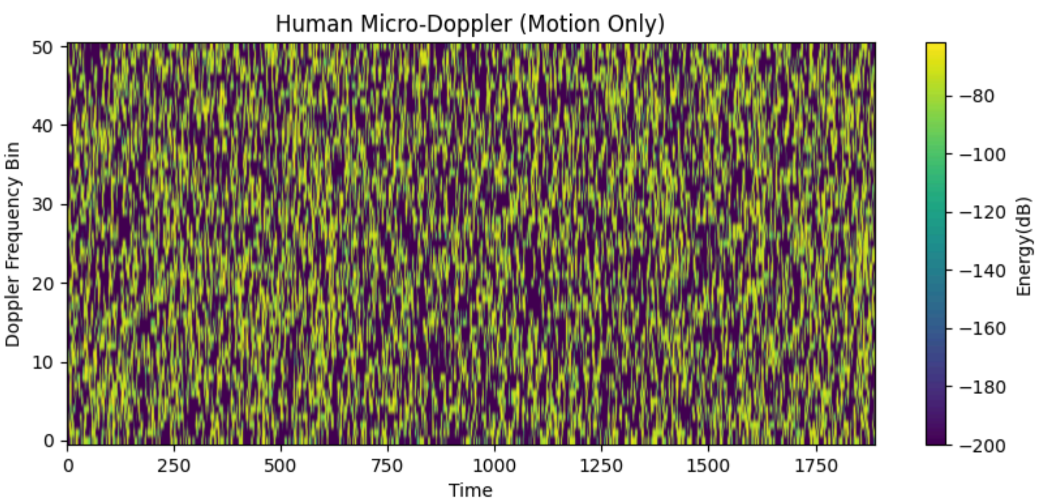
The system was evaluated in a normal indoor room using low-cost hardware.

- A laptop speaker continuously played the 18 kHz ultrasonic probe signal.
- A smartphone microphone recorded the reflected audio.
- Recordings were taken under two conditions:
    - Empty room
    - Human present and moving

- Each recording lasted several seconds and was saved as a WAV file.
- Multiple recordings were collected for each condition to form a dataset.
- All recordings were processed using the same Doppler extraction and feature pipeline.
- Each sample was labeled as empty (0) or human present (1) for training.

This setup demonstrates that accurate Doppler-based sensing is possible using only everyday devices.

➢ RESULT



(Micro-Doppler spectrogram showing human motion around the 18 kHz ultrasonic carrier)

When a human is present, the reflected signal exhibits time-varying energy across multiple Doppler bins, corresponding to movements of different body parts such as arms, torso, and legs. These micro-Doppler signatures form distinct patterns that are absent in empty-room recordings, which show only a narrow and nearly stationary reflection at the carrier frequency.

The extracted Doppler features capture this difference in both temporal and spectral domains, enabling the machine learning classifier to separate empty and occupied states. Even with a small dataset, the system demonstrates consistent detection of human presence, validating the physical sensing principle and the signal processing pipeline.

➢ PRIVACY ANALYSIS

Unlike cameras or conventional microphones, this system does not capture or process semantic information.

- The transmitted probe signal is ultrasonic and monotone (around 18 kHz).
- The recorded audio is analyzed only within a narrow frequency band around this carrier.
- Human speech (300–3000 Hz) lies far outside this band and is completely ignored.
- No voice characteristics, words, or identity-related features are recorded or stored.
- The system uses only motion-induced Doppler frequency shifts to perform sensing.

➢ CONCLUSION

This project demonstrates that acoustic micro-Doppler sensing provides an effective and privacy-preserving method for indoor human activity detection. By combining ultrasonic signal transmission, Doppler-based feature extraction, and machine learning, the system reliably distinguishes between empty and occupied environments using only physical motion cues. The results show that low-cost acoustic sensing can offer a practical alternative to cameras and microphones for privacy-sensitive indoor monitoring applications.