CONIX RESEARCH CENTER

Computing On Network Infrastructure for Pervasive Perception, Cognition and Action

UWHear: Through-wall Extraction and Separation of Audio Vibrations Using Wireless Signals

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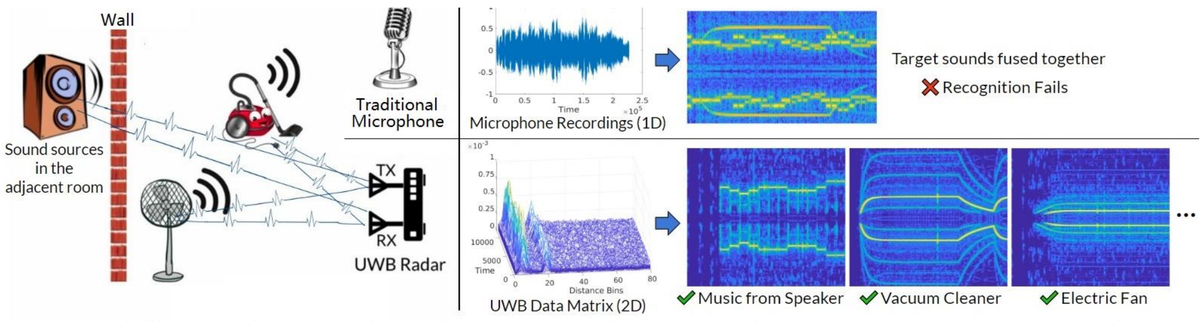
Introduction



- An ability to detect, classify, and localize complex acoustic events can be a powerful tool to help smart systems build context-awareness
- Traditional Solution: Microphone
- Non-target noise may downgrade the performance of audio systems
- Multiple target sounds are blended into a single audio recording, and are difficult to recognize or separate

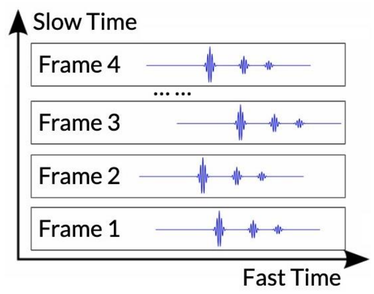
✓ **UWHear: An acoustic sensing system built with Impulse-Radio Ultra-Wideband (IR-UWB) Radar**

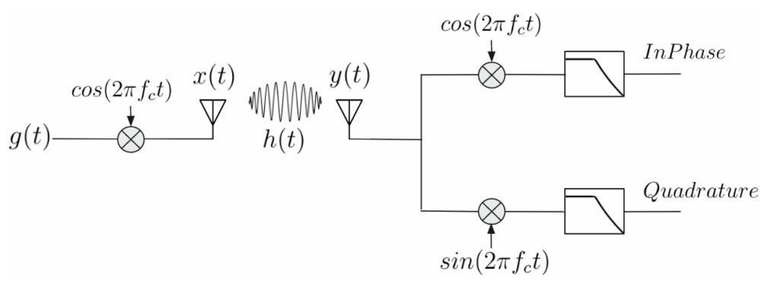
- Operates by sending a train of ultra-short pulses and analyzing responses
- Recovers sound directly from source vibrations
- Can collect multiple target sounds separately and simultaneously by measuring the distance between the sensor and the sound sources
- Can operate through-wall / in None-Line-of-Sight (NLOS) conditions

System Design

Notion of Fast Time and Slow Time:

- The data collected by UWHear is two-dimensional. We define a frame as a period where one pulse is sent out and its responses are collected.
- Time t within one frame corresponds to the time-of-flight (ToF) of the signal pulse, which is also known as **fast time**.
- IR-UWB sequentially transmits probe pulses with interval T_s. We use **slow time** to denote the probe pulse repetition intervals.



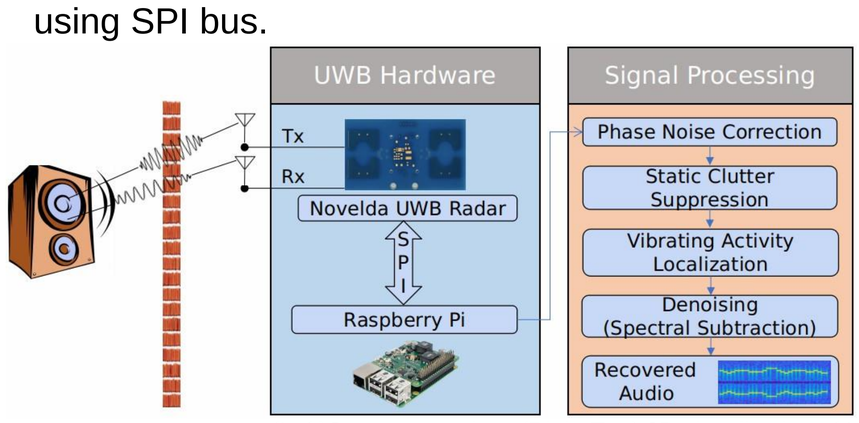


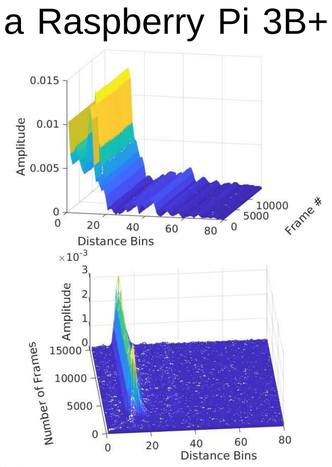
UWB Sound Recovery Theory:

- Fast time represent the ToF of the pulses, which can be translate into target distance. We slice the 2D data in the fast time domain to obtain multiple time streams, each representing a distance bin. Thus we can **separate multiple target sound sources** spatially using ToF.
- We prove mathematically using the baseband equivalent model that, the sound source vibration displacement is linearly proportional to the amplitude of the Quadratic or In-phase part of the UWB receiving signal.

UWHear Hardware:

- Novelda Xethru X4M05 IR-UWB radar board, which operates at a center frequency of 7.29GHz with a bandwidth of 1.4GHz.
- The radar board is controlled by and export data to a Raspberry Pi 3B+ using SPI bus.





(Left)System overview. (Right Top) 3D visualization of UWHear raw data. (Right Bottom) 3D visualization of UWHear data after processing.

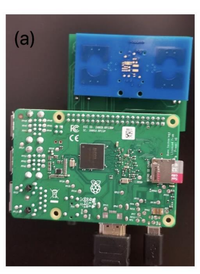
UWHear Signal Processing Pipeline:

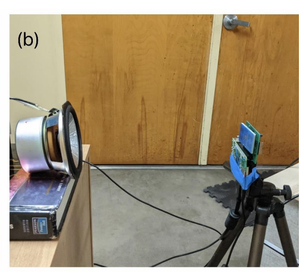
- **Phase Noise Correction:** Calibration that removes phase jittering caused by sampling clock inaccuracy
- **Static Clutter Suppression:** Filtering that suppresses the reflections caused by static objects
- **Vibration Activity Localization:** Algorithm that identifies the distance bins that potentially contains vibrating sound sources based on spectrum concentration (using Herfindahl-Hirschman index)
- **Denoising:** Linear Spectral Subtraction that battles additive noise

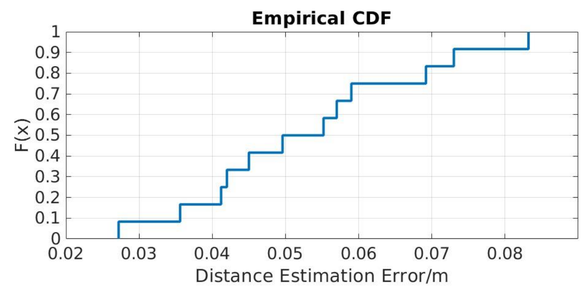
Results

Sound Source Distance Measurement:

UWHear can give an accurate distance estimation of sound sources. The mean error is 5.31cm, the median error is 5.24cm, the maximum error is 8.32cm, and the standard deviation is 1.63cm.

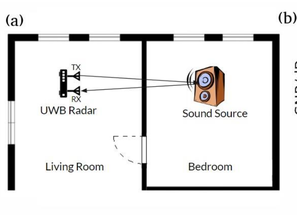


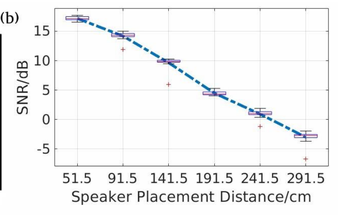


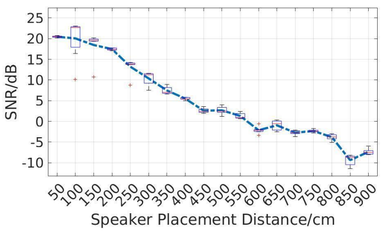


Operating Through-wall / in NLOS Conditions:

UWB radar signal can penetrate materials like the wall between the living room and the bedroom. UWHear can recovered sound from more that 2m away through wall with a reasonable SNR. The effective sensing range is 6-8m in free space.

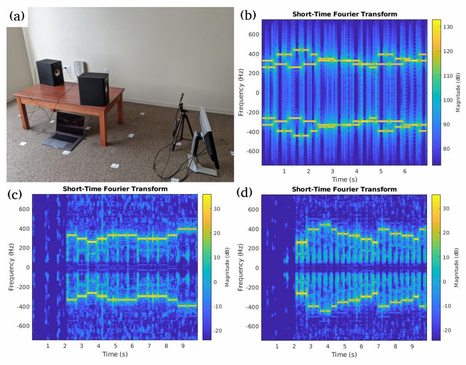


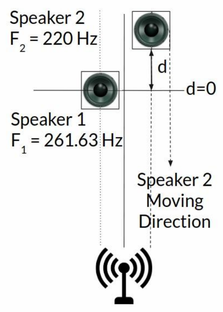


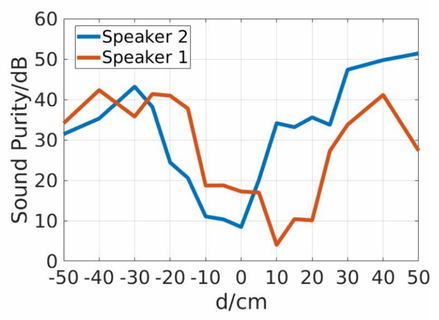


Multiple Target Sounds Separation:

In this experiment, two speakers playing different music are placed in front of the UWHear hardware. The music played are entangled both in the time domain and the frequency domain.



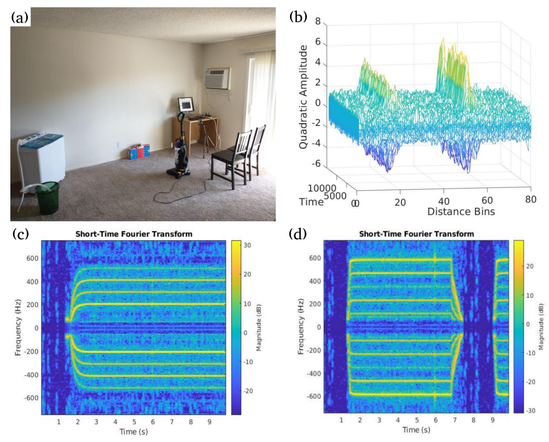




Results demonstrate that if two sources are placed 25 cm apart, their sounds can be recovered separately with out any cross-interference

Dealing with Heterogeneous Sound Sources

- UWHear can deal with the sound from heterogeneous sources.
- In this experiment, we test UWHear in a more natural home environment: (a) a setting with washing machine, vacuum cleaner and wall AC unit operating at the same time.
- From the processed UWHear data matrix (b), we can obtain the recovered sound for the vacuum cleaner(c) and washer machine (d), without any interference from the AC unit or each other.



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