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

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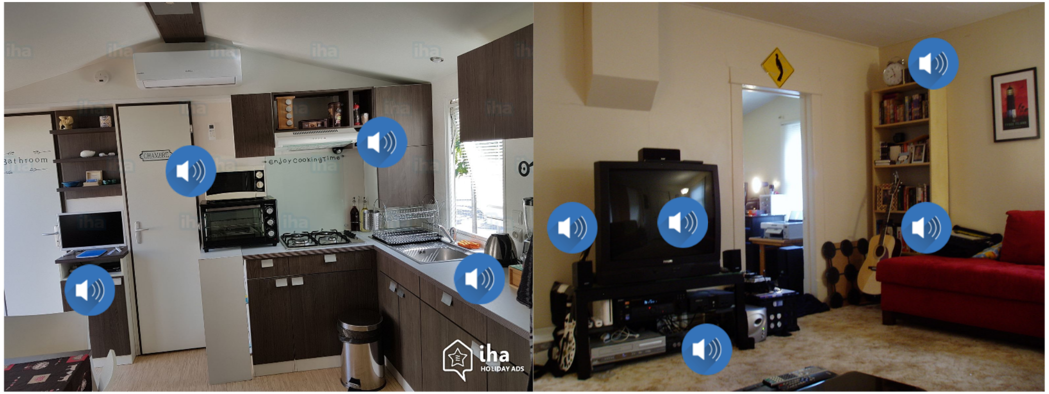
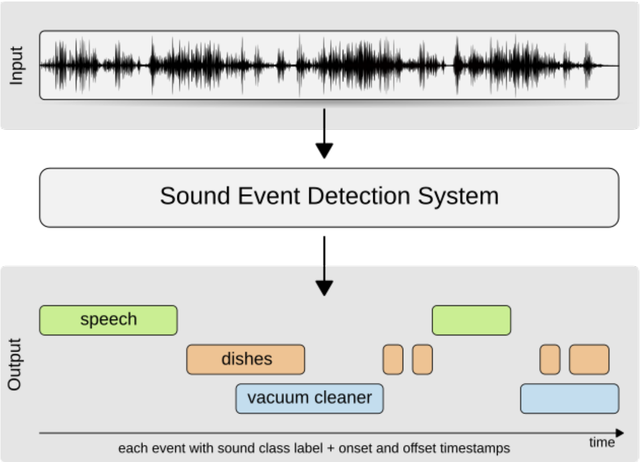
Audio Sensing and Sound Event Detection

- An ability to detect, classify, and localize complex acoustic events can be a powerful tool to help smart systems build context-awareness





A typical example of sound event detection and classification systems. Flow chart from http://dcase.community/challenge2019/task-sound-event-detection-in-domestic-environments

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Dual Challenges for Audio Sensing

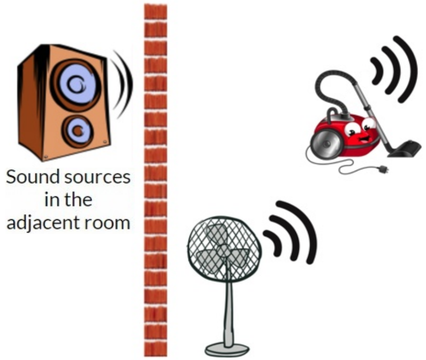
Noise / Non-target sound

Multiple Target Sounds

- Audio sensing and downstream processing are negatively affected by background noise and cross-interference between target sound sources.

Goal: Separate Sound from Multiple Sources

- A desired audio sensing system should be able to:



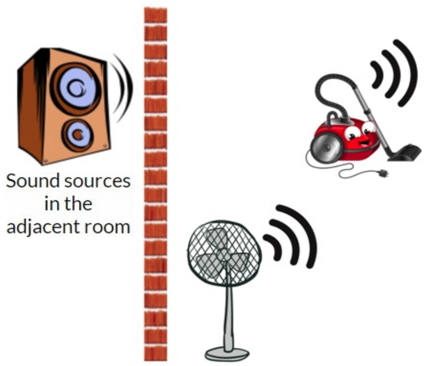
① Record audio signals from vibrations

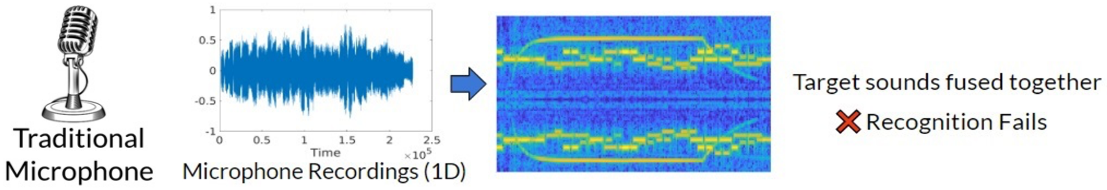
② Separate sounds from multiple sources

③ Work in non-line-of-sight (NLOS) scenarios

Audio Sensing: Microphone vs Wireless Signals

- A traditional microphone passively captures the sound pressure wave.
- Multiple target sounds and noise are blended?

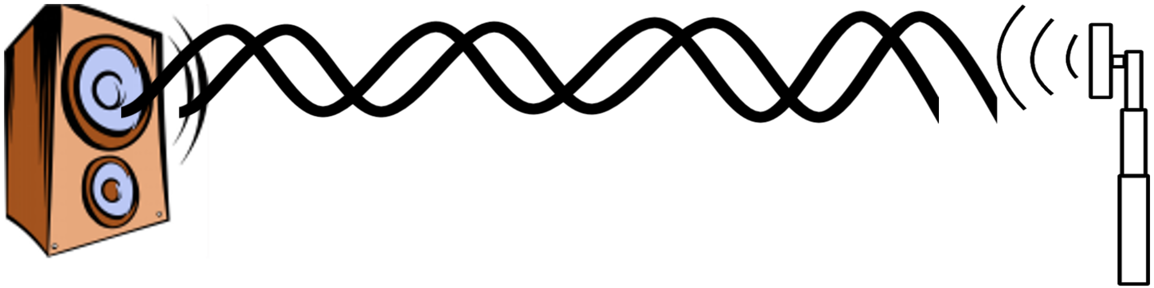




- Can we actively measure the sounds from their source vibrations?

Wireless Vibrometry

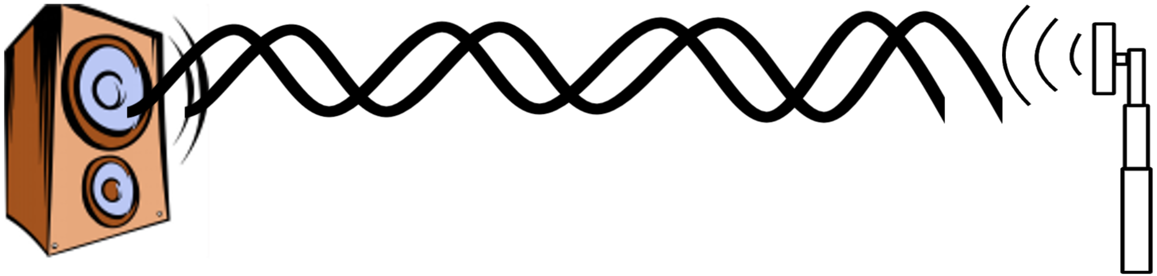
- Wireless Vibrometry is about recovering information from vibrating objects, e.g. speakers, engines…....



- Can be used to recover sound directly from its source vibrations
  - Previous works isolates one sound of interest by focusing a **highly directional beam** on its source

Wireless Vibrometry Using IR-UWB Radar

- Impulse-Radio Ultra Wideband (IR-UWB) works by sending out a train of very short Gaussian pulses and collect reflection pulses.



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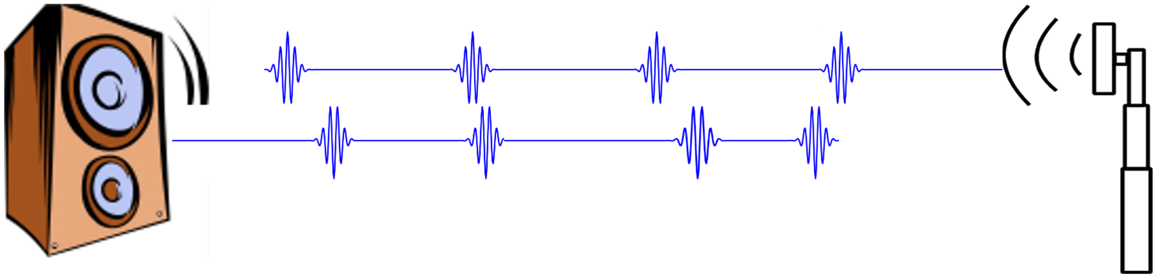


Wireless Vibrometry Using IR-UWB Radar

- Impulse-Radio Ultra Wideband (IR-UWB) Radar

Sound Separation
  - Operates with very short pulses (large bandwidth)
  - Has fine spatial resolution to separate multiple sources
  - Measures the distance to the targets with Time-of Flight

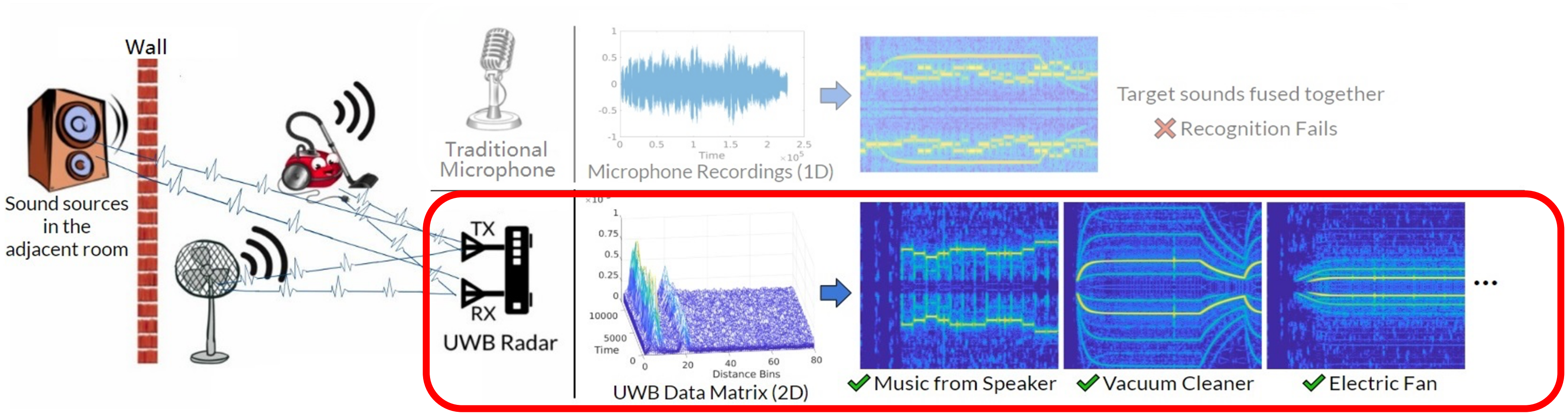
Sound Recovery
  - Can detect subtle target movements with RF phase
  - (To be shown in the next section)

NLOS
  - Works at sub-10GHz band
  - Can Penetrate light building materials

Practical
  - Is incorporated on mobile platforms (e.g., iPhone 11)
  - Is low-cost and has low power consumption

Audio Sensing: Microphone vs Wireless Signals

- **UWHear** is a system that uses Impulse Radio Ultra-Wideband (IR-UWB) to separate and recover sounds from multiple sources simultaneously.



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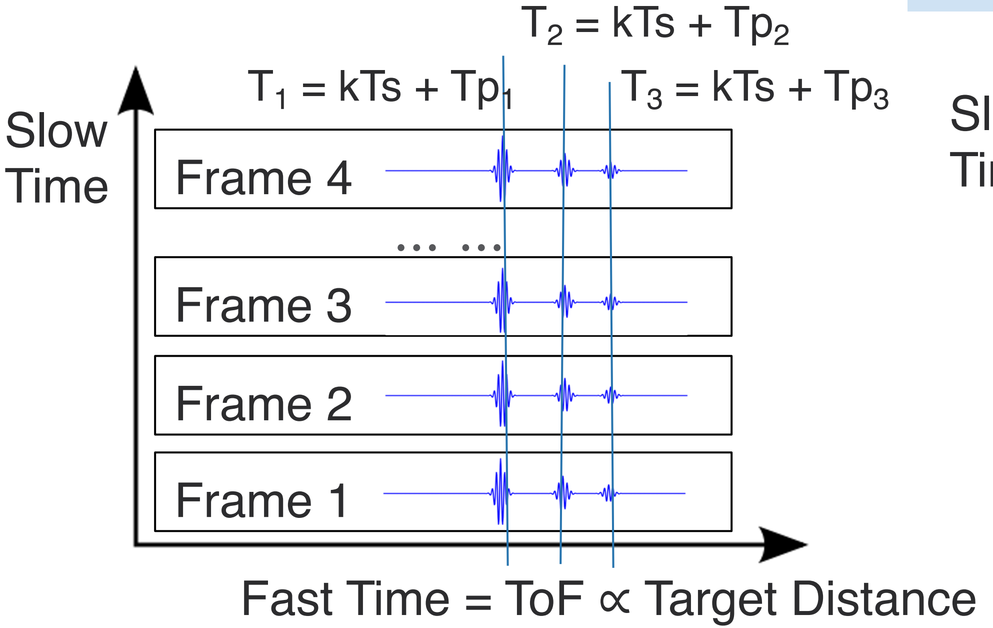
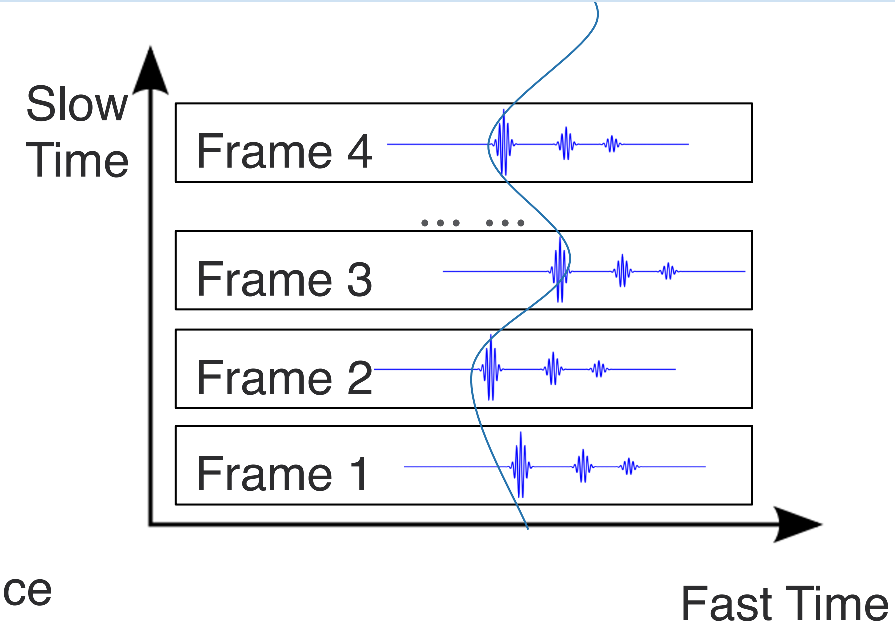
IR-UWB Audio Sensing Theory

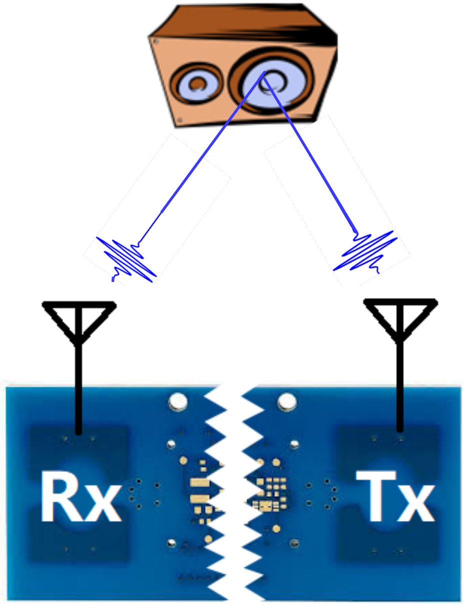
Data Structure: Fast time and Slow time

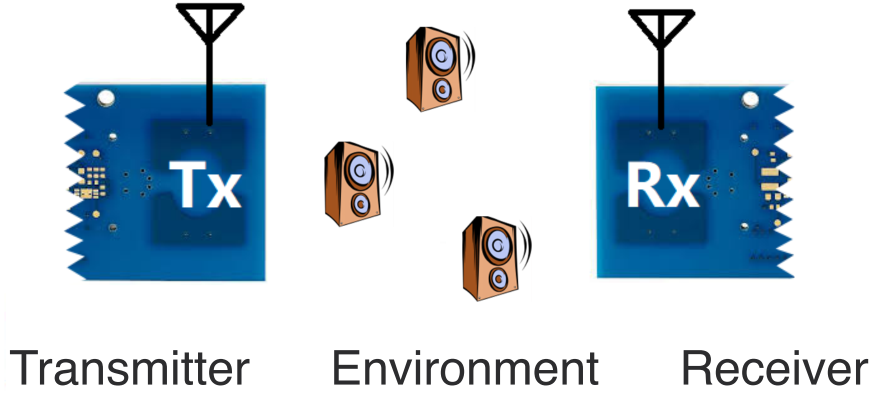


Challenge: Speaker displacement ~mm level, UWB spatial resolution ~cm level

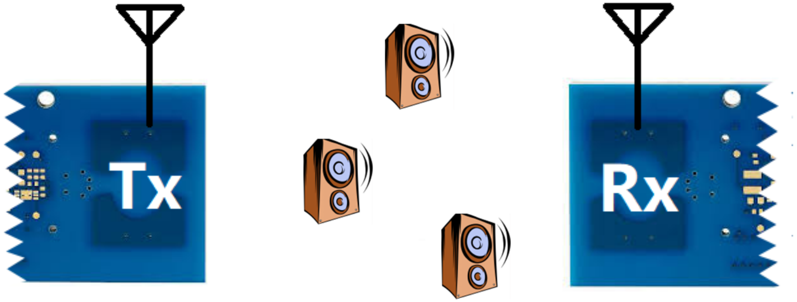


IR-UWB Audio Sensing Theory

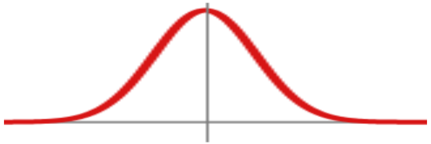




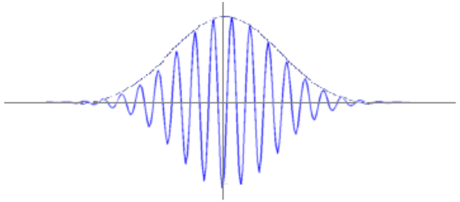
IR-UWB Audio Sensing Theory



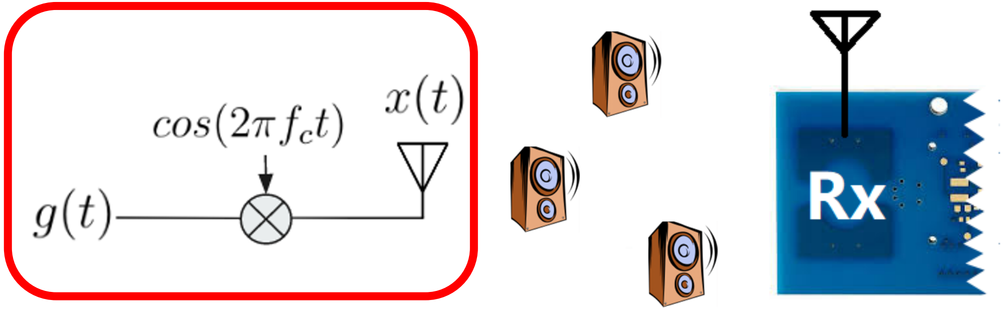
Baseband Gaussian pulse: $g(t)$



Transmitter Output: $x(t) = g(t - kT_s)cos(2\pi f_c(t - kT_s)),$

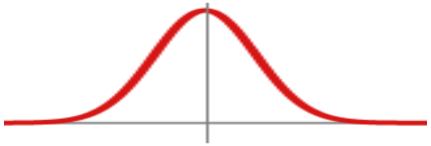


IR-UWB Audio Sensing Theory



Transmitter

Baseband Gaussian pulse: $g(t)$



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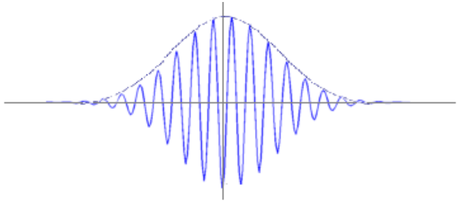
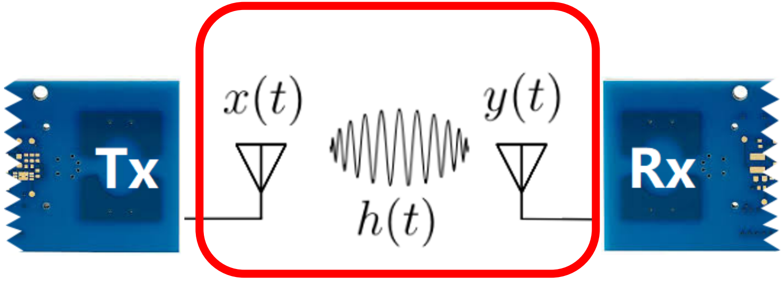


IR-UWB Audio Sensing Theory



Environment

Environment Response

Caused by the placement distance of speaker p

$$h(t) = \sum_{p=1}^{P} \alpha_p \delta(t - \boxed{T_p} - \boxed{T_p^D(t)})$$

Caused by vibration of speaker p

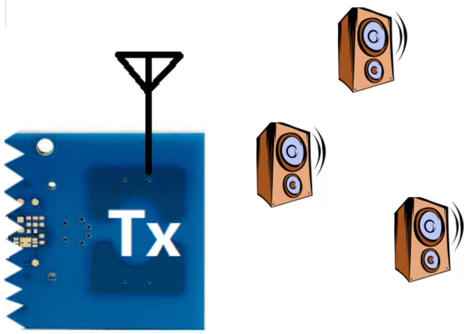
RF Received Signal

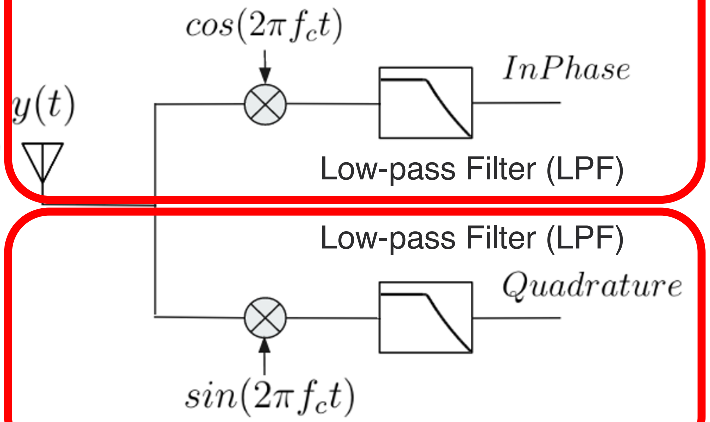
$$y(t) = x(t) * h(t) + n(t)$$

The **phase** of received RF signal is proportional to **speaker vibration**

$$= \sum_{p=1}^{P} \alpha_p g(t - kT_s - T_p - T_p^D(t)) cos(2\pi f_c(t - kT_s - T_p - \boxed{T_p^D(t)})) + n(t).$$

IR-UWB Audio Sensing Theory





Down Conversion (Demodulate) to Baseband:

$$y_{in-phase}(t) = LPF[y(t) \times cos(2\pi f_c(t - kT_s))]$$

$$y_{quad}(t) = LPF[y(t) \times sin(2\pi f_c(t - kT_s))]$$

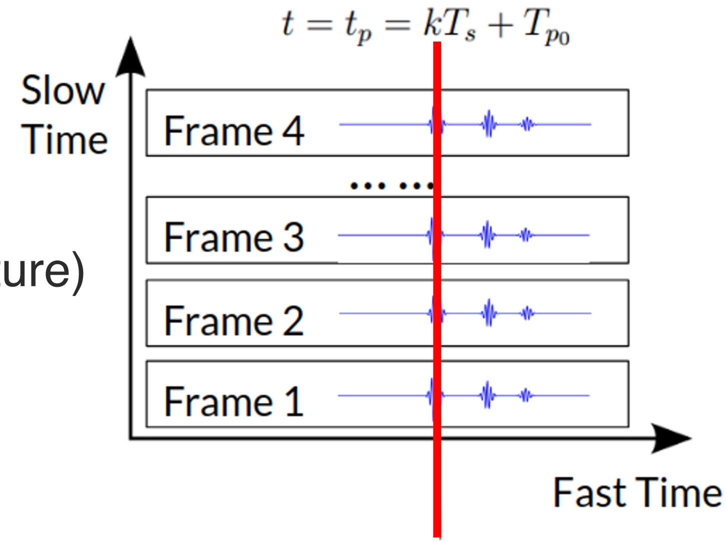
Apply Sound Source Separation using ToF

Apply sound source separation

Select a particular sound source by fixing $t = t_p = kT_s + \boxed{T_{p_0}}$

ToF caused by the placement distance of speaker p_0

Data Matrix
(In-phase or Quadrature)



Linear Approximation

- The I/Q data $\approx V_{\text{tx}}$

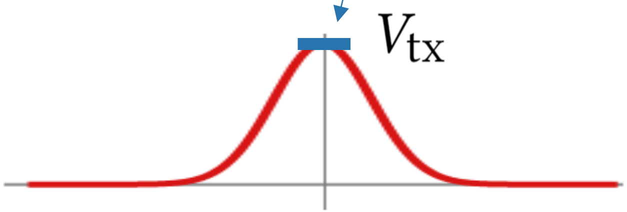
Time-varying phase offset caused by speaker p_0 vibration

$$y_{in-phase}(t_p) = \frac{1}{2}\alpha_{p0}\boxed{g(T_{p0}^D(t_p))}cos(\boxed{2\pi f_c T_{p0}} + \boxed{2\pi f_c T_{p0}^D(t_p)}) + \tilde{n}(t_p).$$

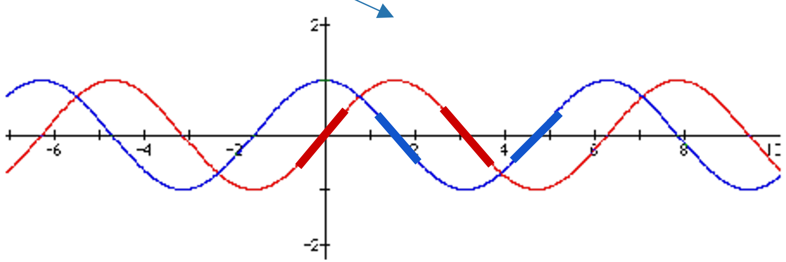
Constant phase offset caused by the distance of speaker p_0

$$y_{quad}(t_p) = \frac{1}{2}\alpha_{p0} g(T_{p0}^D(t_p))sin(2\pi f_c T_{p0} + 2\pi f_c T_{p0}^D(t_p)) + \tilde{n}(t_p).$$

- Linear approximation



Gaussian Pulse

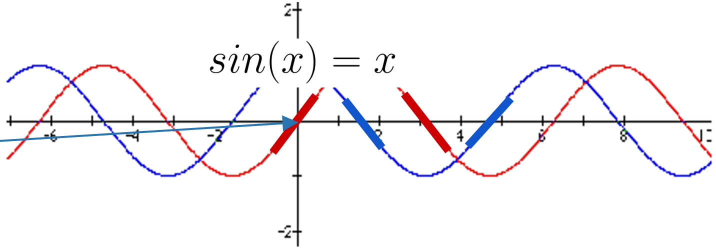


Sine and Cosine Function

IR-UWB Audio Sensing Theory

$$y_{\text{in-phase}}(t_p) = \frac{1}{2}\alpha_{p_0} V_{\text{tx}} \cos\left(2\pi f_c T_{p_0} + 2\pi f_c T^D_{p_0}(t_p)\right)$$

$$y_{\text{quad}}(t_p) = \frac{1}{2}\alpha_{p_0} V_{\text{tx}} \sin\left(2\pi f_c T_{p_0} + \underline{2\pi f_c T^D_{p_0}(t_p)}\right)$$



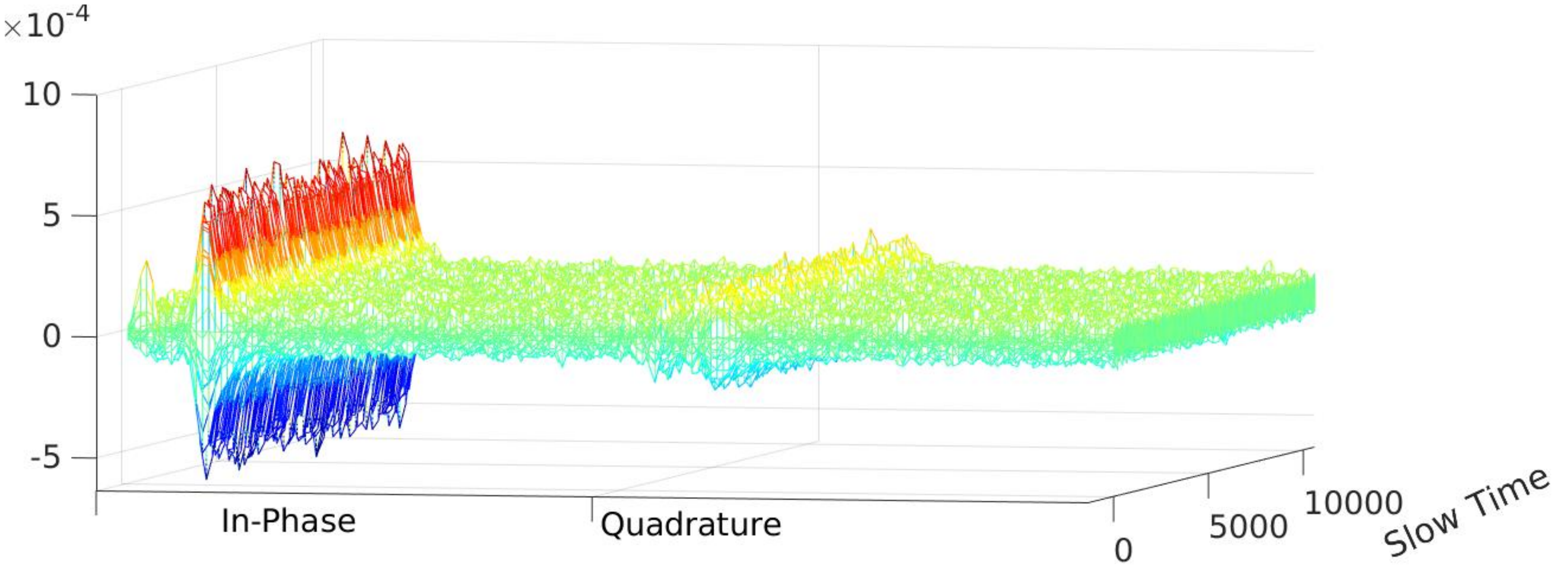
- Linear approximation

- Example: $mod(2\pi f_c T_{p_0}, 2\pi) \approx 0$

$$y_{quad}(t_p) = \frac{1}{2}\alpha_{p_0} V_{TX} 2\pi f_c T^D_{p_0}(t_p)$$

- In this example, the **speaker vibration movement** is proportional to **quadrature amplitude** change
- In other cases, the speaker displacement is proportional to **in-phase** amplitude change

IR-UWB Audio Sensing Theory



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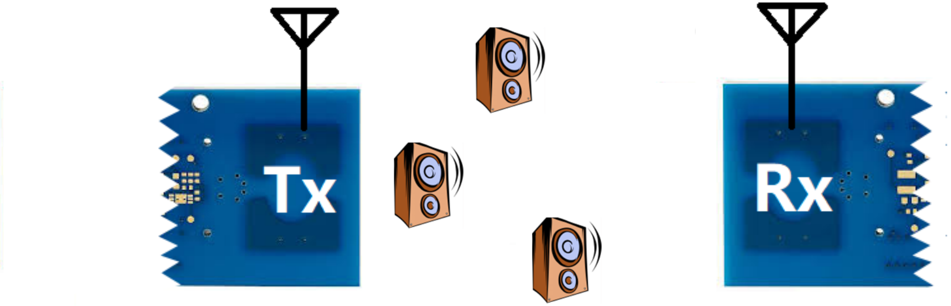

Transmitter Environment Receiver

Gaussian Pulse → Transmitted RF Pulse → Received RF Pulse → Baseband I/Q Signal

Subtle ToF Change

Time-varying Phase

In-phase/Quadrature Amplitude

IR-UWB Signal

Vibration-related Information

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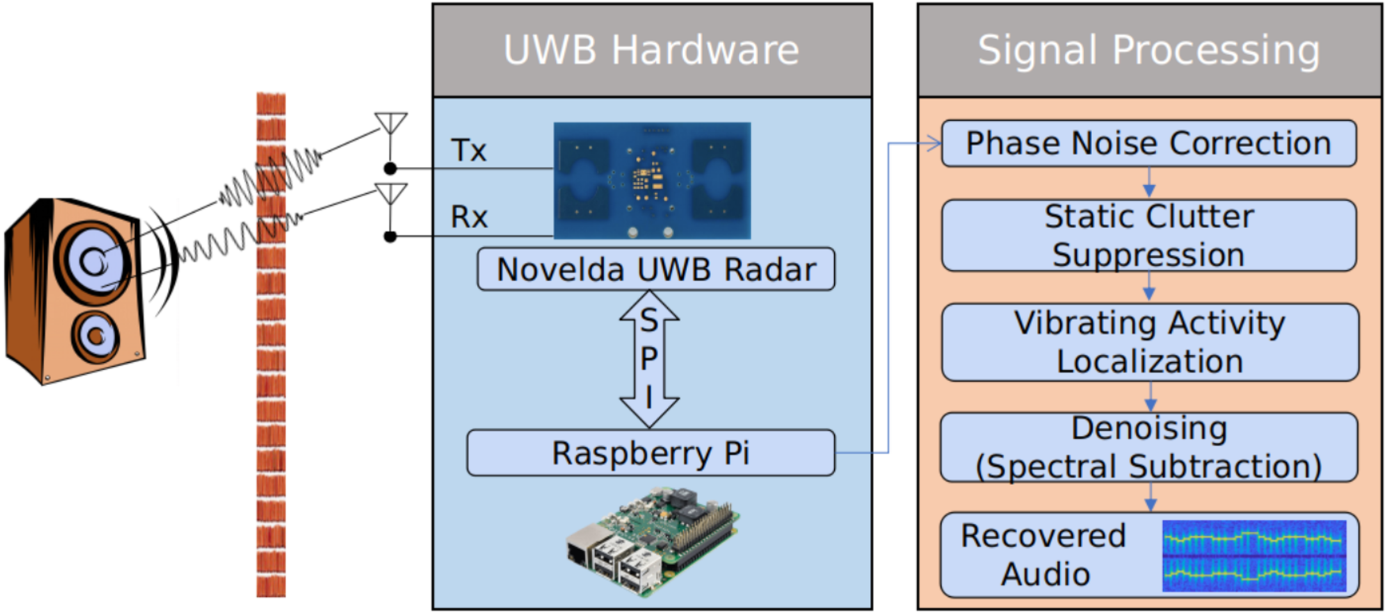
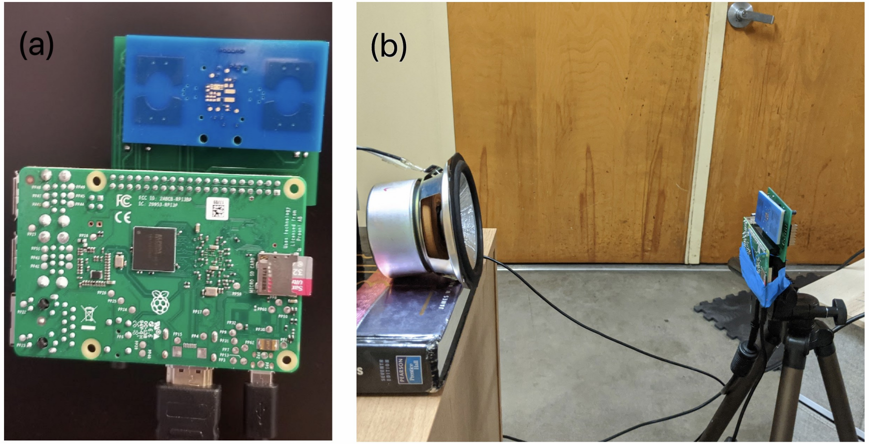
UWHear System Design

System Overview



Hardware Implementation

- XeThru X4M05 UWB Radar Sensor
- Controlled and sending data to Raspberry Pi 3B+ via SPI interface
- Gaussian pulses with 1.4 GHz bandwidth centered at 7.29GHz
- Can comply with FCC regulations, Sampling rate 1.5 kHz



Signal Processing Pipeline

Raw UWB Data

Phase Noise Correction

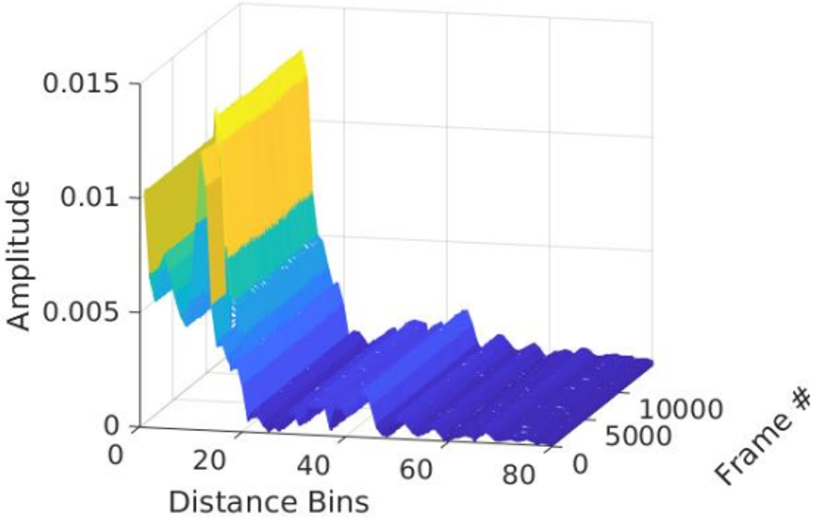
Static Clutter Suppression

Vibrating Target Localization

Spectral Subtraction

Recovered Sound

Further Analysis



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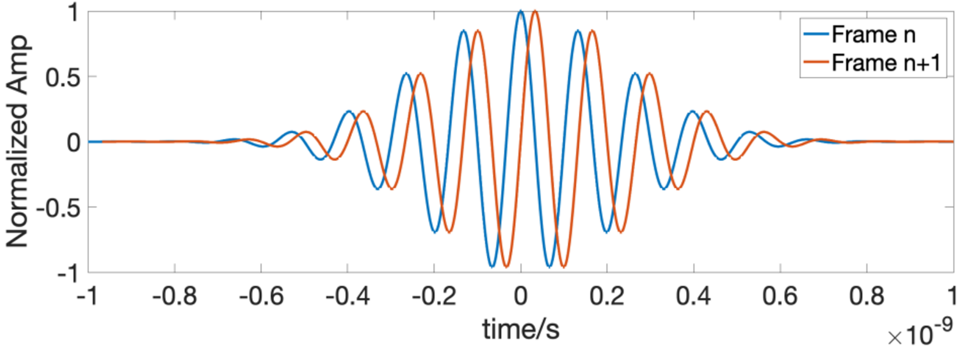

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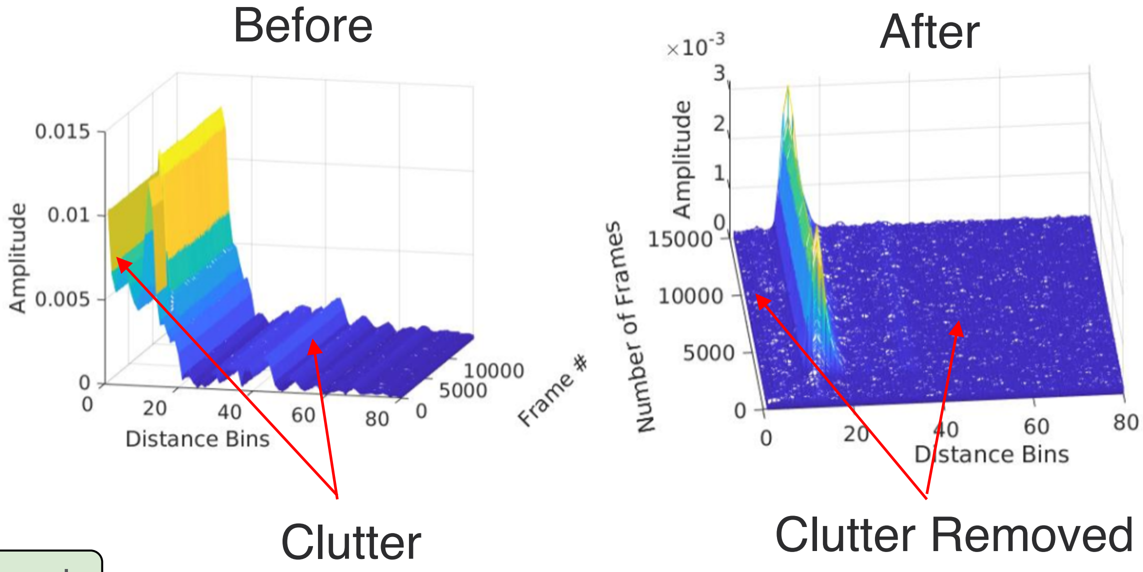

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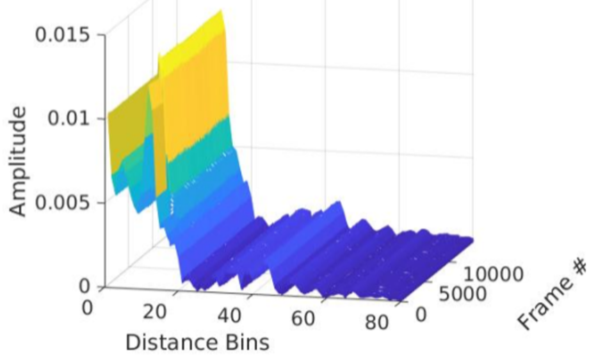
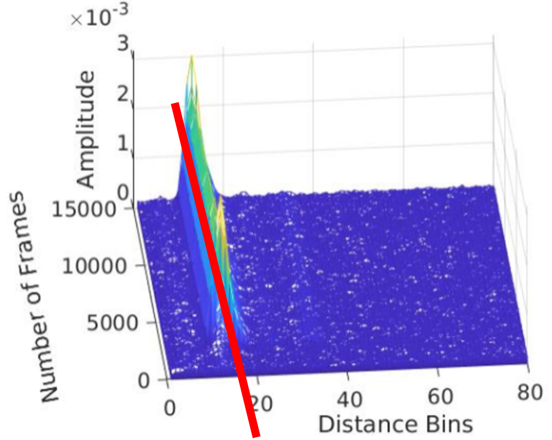
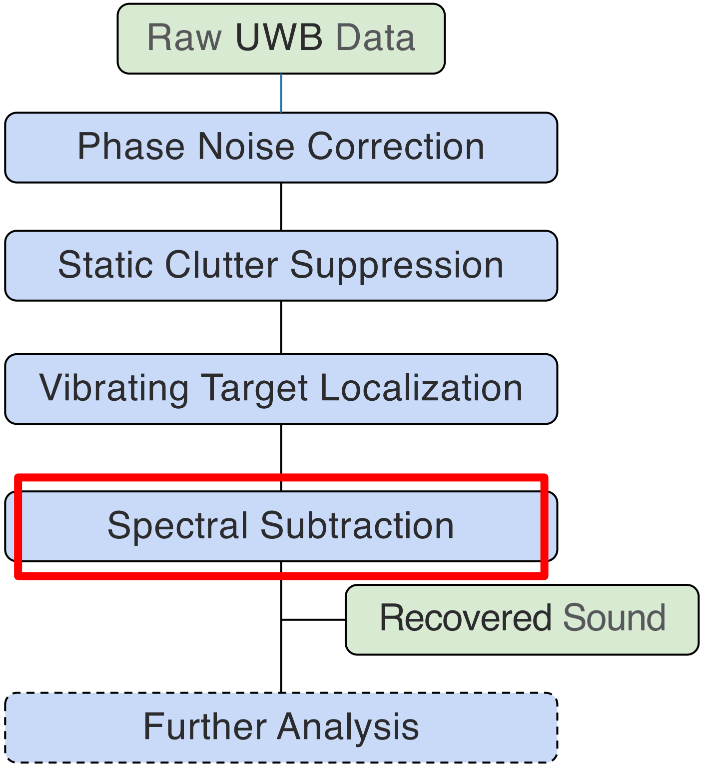
- Spectral Subtraction
  - Recovered Sound
- Further Analysis

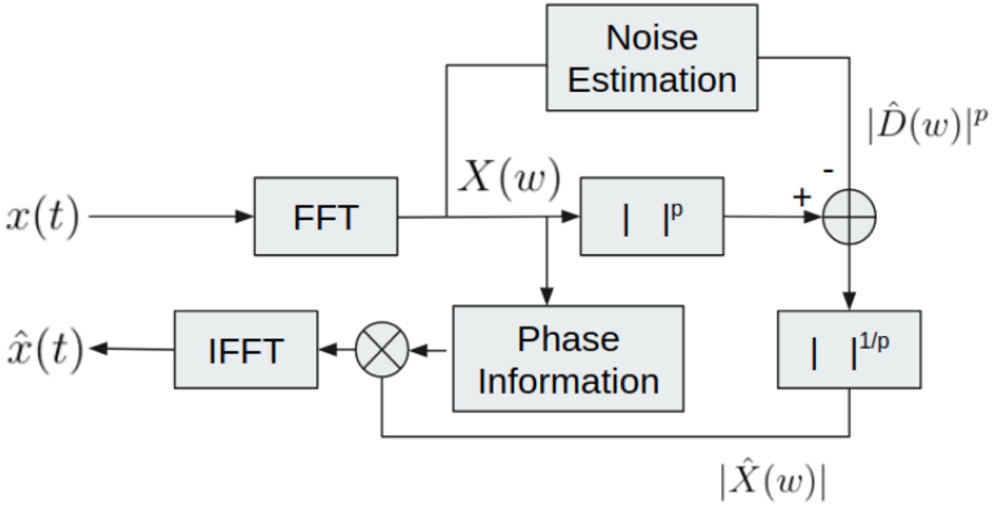




Distance = 1m

Signal Processing Pipeline





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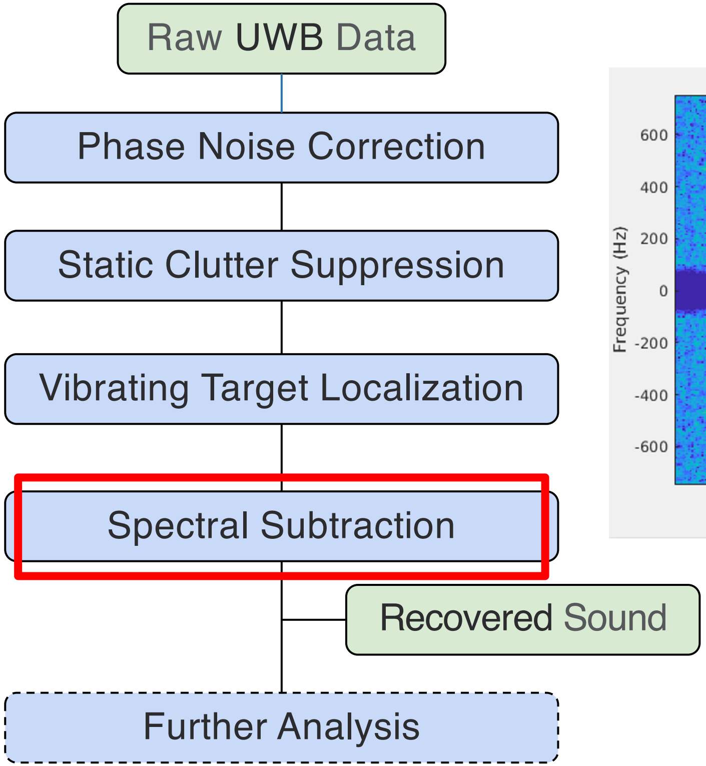

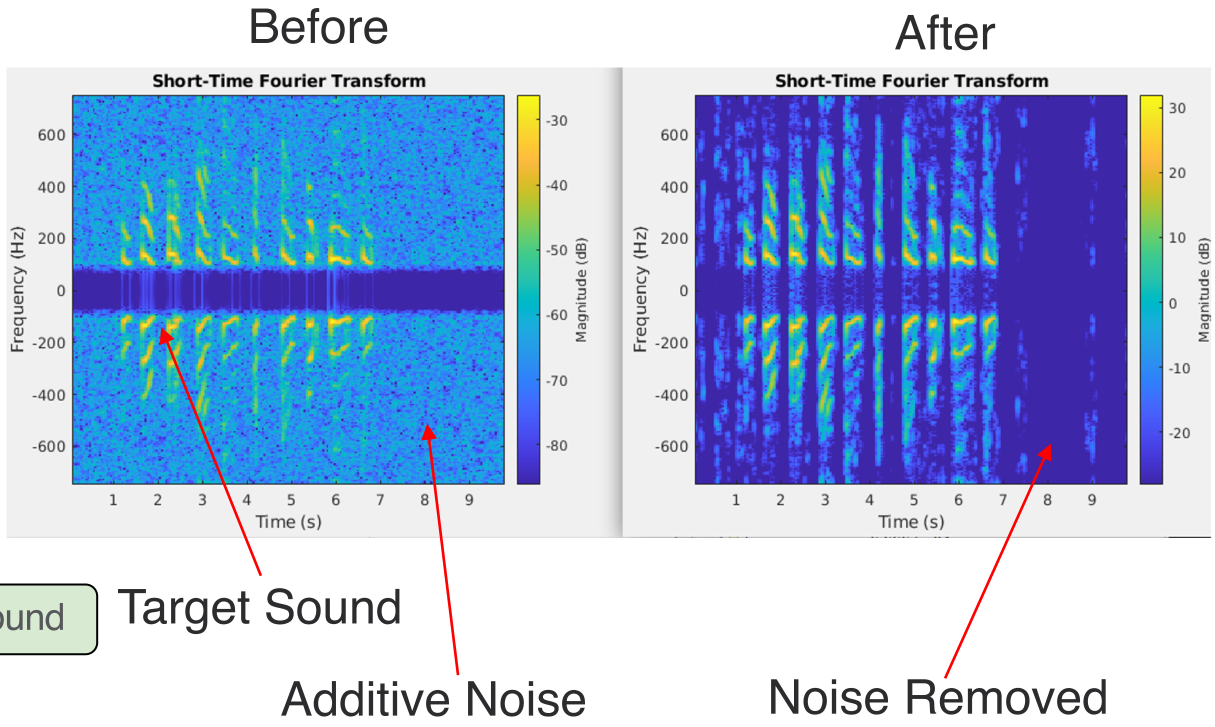

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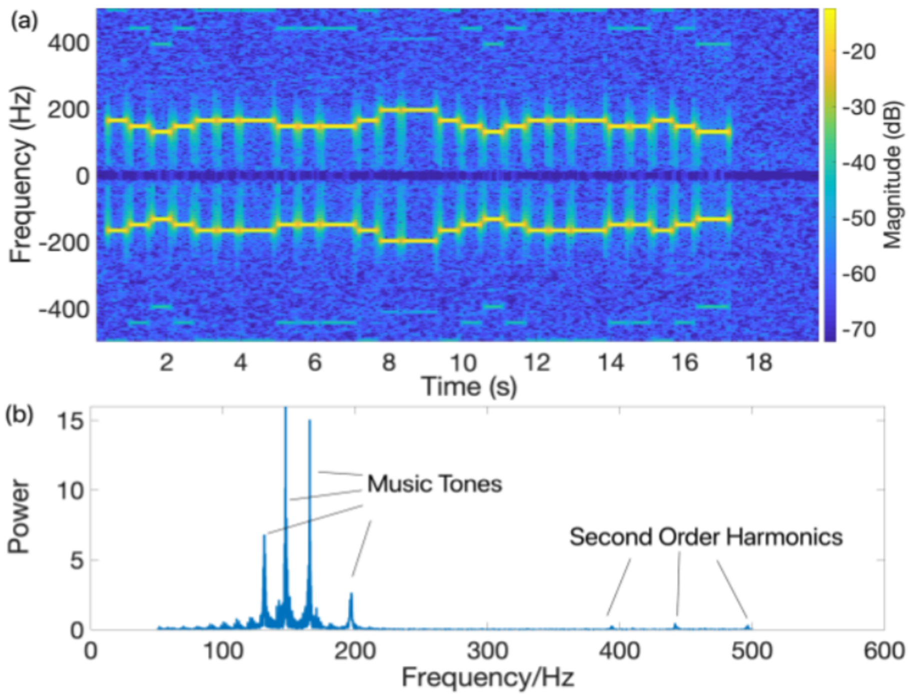

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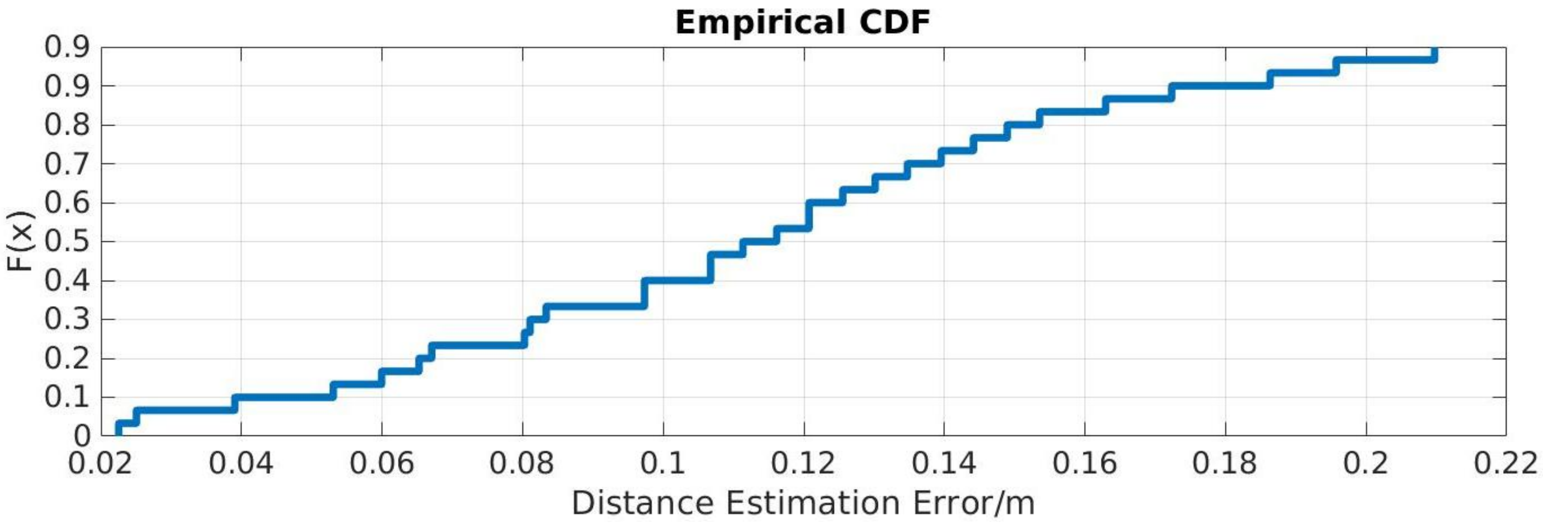
Results

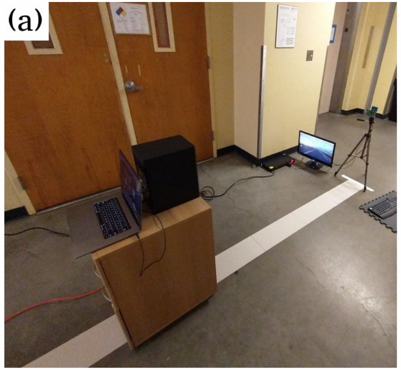
Distance to Sound Sources

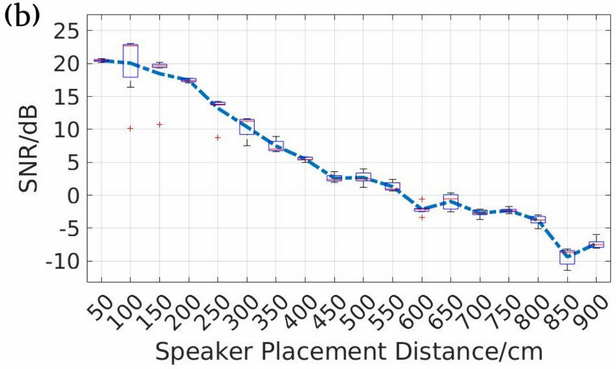
- Measured the distance to the sound sources
- The mean error is 11.19cm, the median error is 11.37cm, σ=4.88cm.

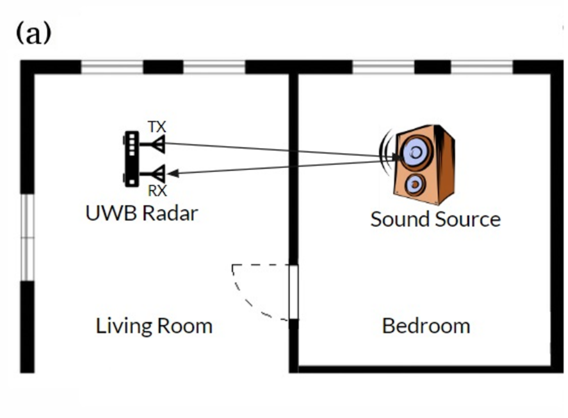


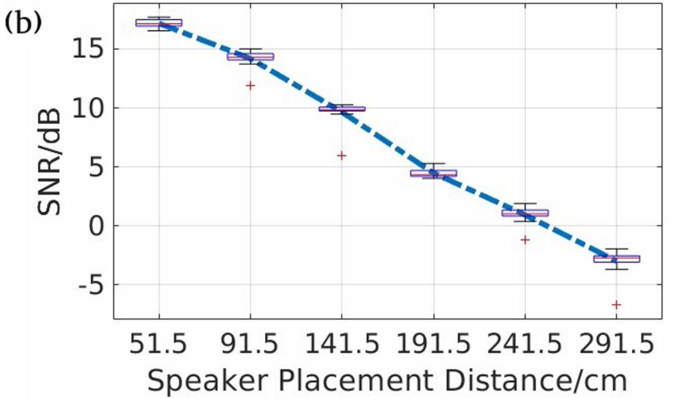
Effective Range

- 6-8m in Free Space
- 2.5m through a wooden wall



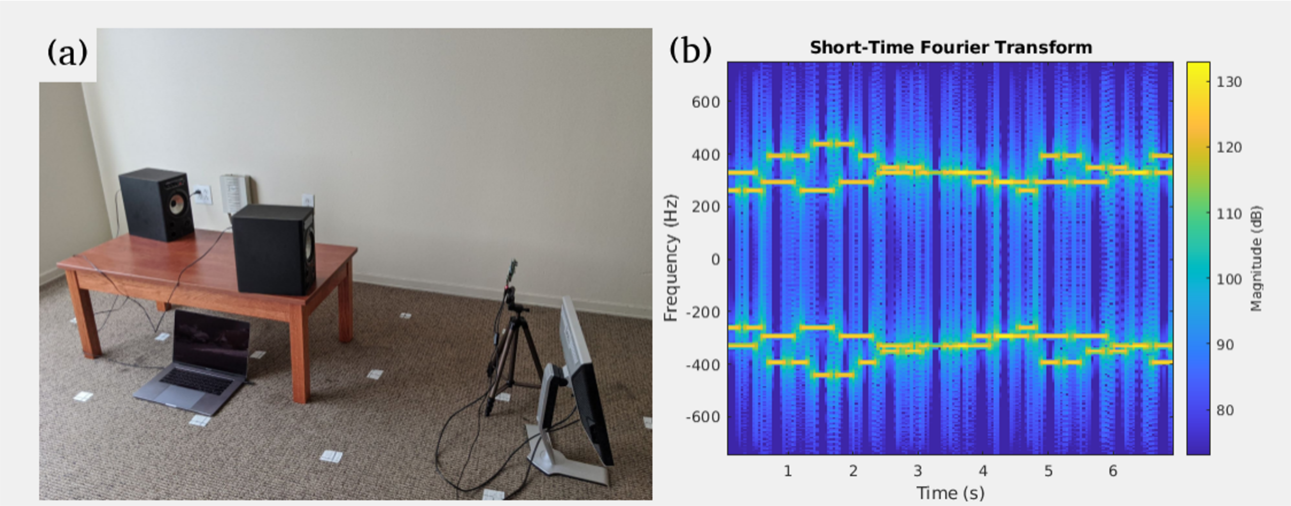




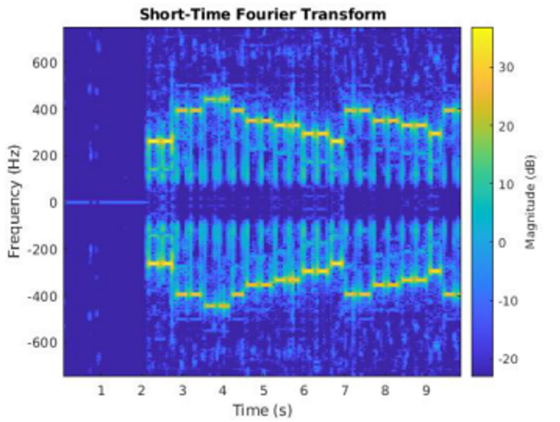


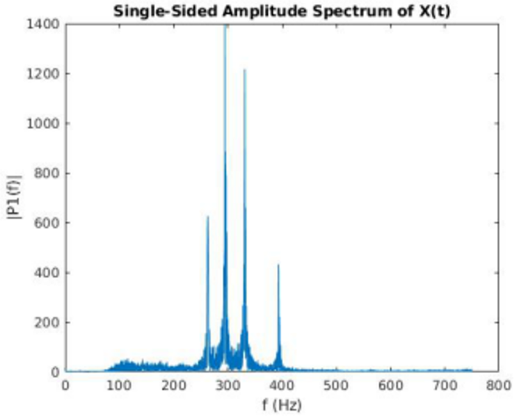
Demo: Sound Separation

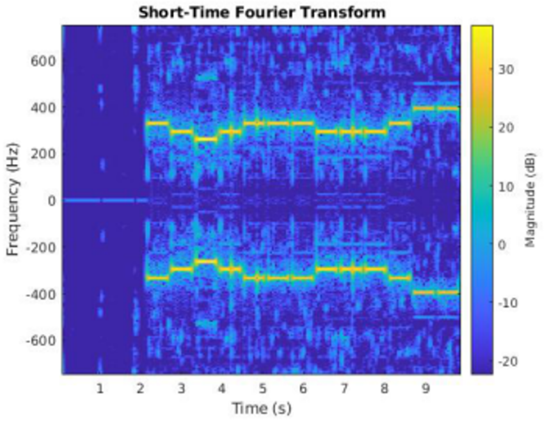
- Two speakers put at different distances and playing different contents
- One at 58cm playing *Mary has a little lamb*
- The other at 122cm *playing Twinkle twinkle little star*
- Please see the demo on the next page

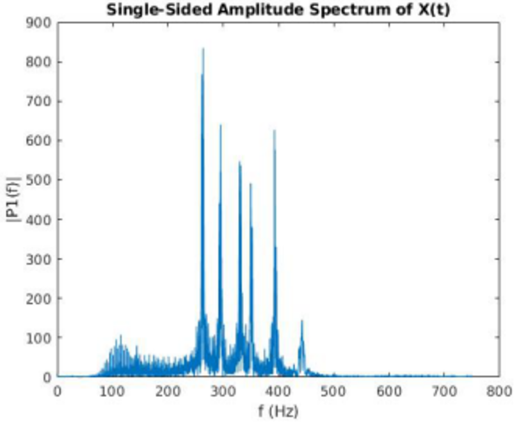


Further results demonstrate that if two sources are placed **25 cm** apart, their sounds can be recovered separately without any cross-interference.



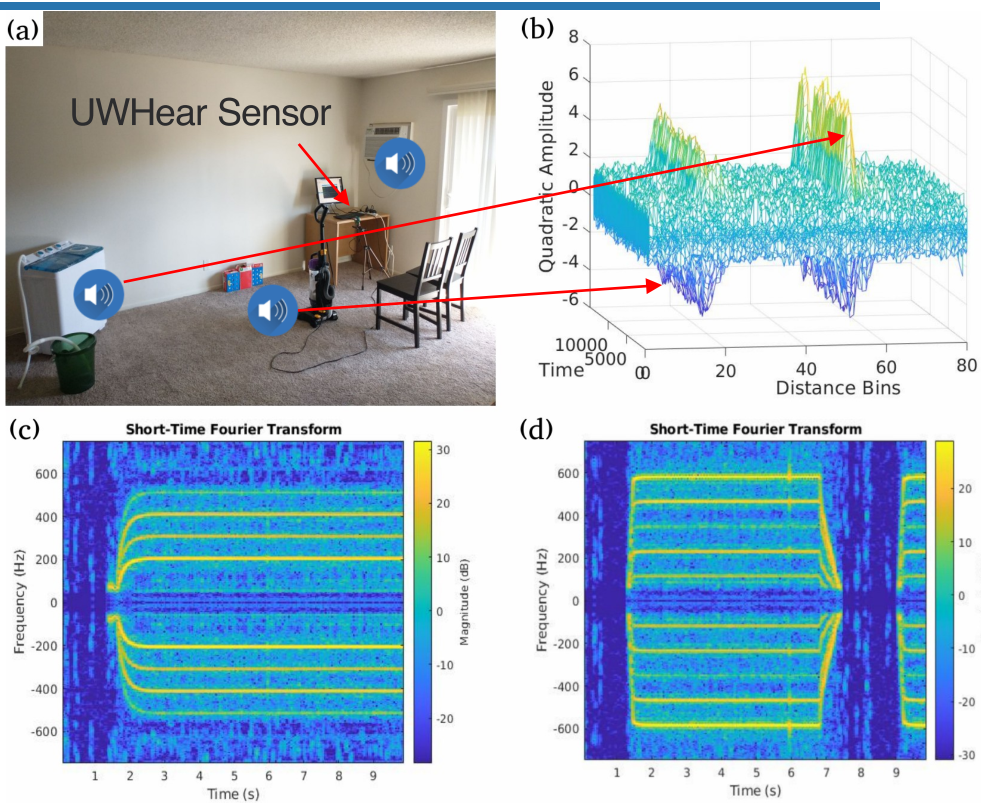






Dealing with Heterogeneous Sound Sources

- We tested UWHear in a more natural household setting
- Sound Source: Washing Machine, Vacuum Cleaner
- Noise Source: Wall AC Unit



Vacuum Cleaner

Washing Machine

Limitations and Future Work

- Increase Sampling Rate:
  - The current sampling rate (Fs = 1.5kHz) causes low sound quality
  - Fs is mainly limited by the SPI interface transmission speed
  - Using FPGA as the host may help

- Increasing Field-of-View (FoV)
  - Current directional antenna gives 50 degrees of FoV
  - Novel hardware design may use omnidirectional antenna / MIMO

- Multi-model Sensing Platform
  - UWHear cannot retrieve sound from human throat directly
  - Multiple Wireless Signals at different bands can compensate for each other
  - IR-UWB has more potentials then sensing vibration

Thank you!

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