Desk Occupancy Estimation Assisted with Low-Power Backscatter Tags

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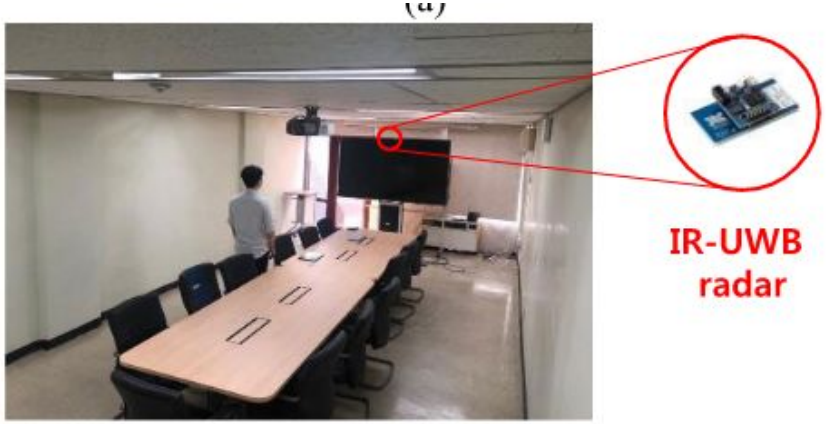
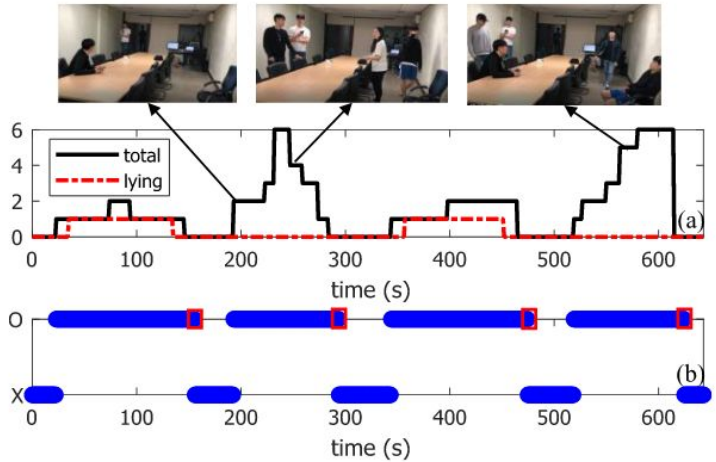
Motivation

- Smart workspace calls for accurate, ubiquitous desk-level occupancy status
- Previous device-free system rely on Wi-Fi is insufficient to provide desk-level precision without needing heavy fingerprinting
- Next-Gen WiFi APs (e.g., from CISCO) would equip Ultra-WideBand (UWB) Radios, which provide much high bandwidth and better range resolution
- **Goal:** achieve accurate desk occupancy estimation without heavy fingerprinting

Related Works

- UWB based detection of presence of Individuals in an room
- Only provide binary label at a room level (people presence or not)





Robust Detection of Presence of Individuals in an Indoor Environment Using IR-UWB Radar

Related work:

- People counting for a bus
- Accuracy drop from 91.5% to 34.1% when moving from a lab bus to the real bus

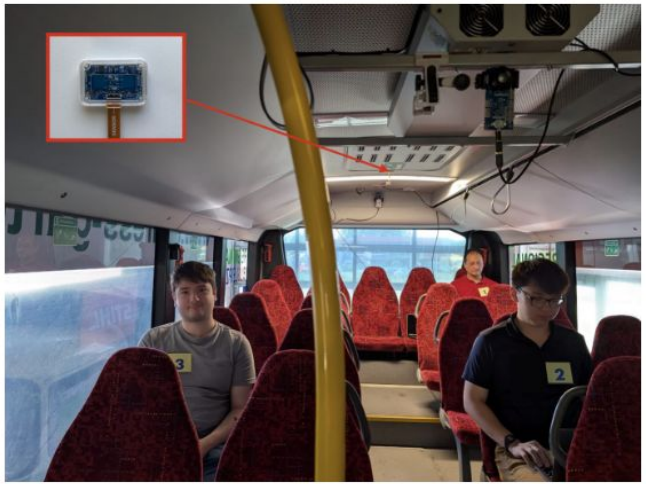
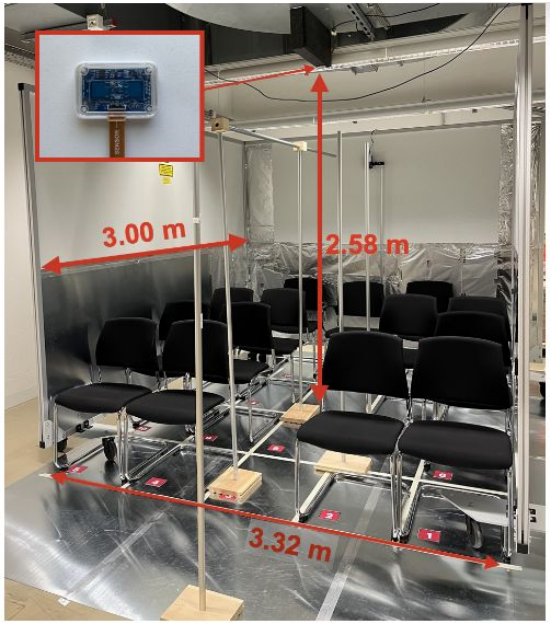
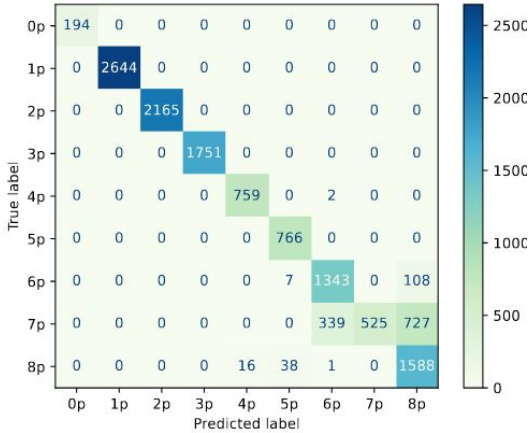


Fig. 1: Experimental setup of the Real Bus scenario.



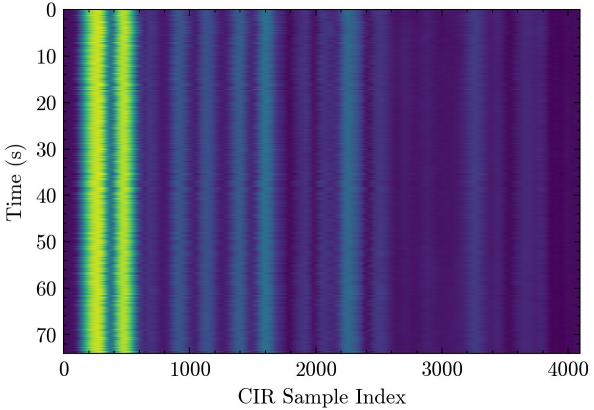


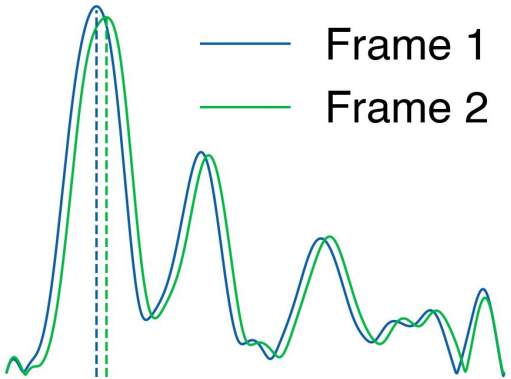
DeskPulse

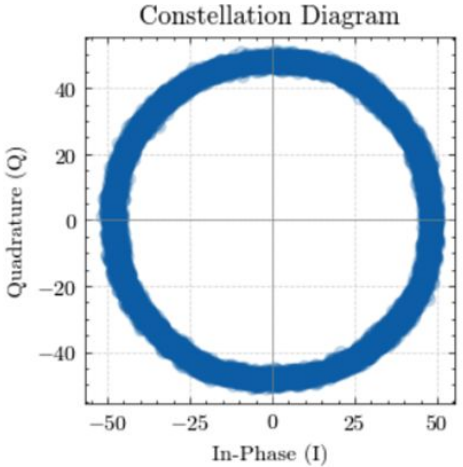
- We propose a signal processing pipeline that calibrate the hardware imperfections of COTS devices, effectively achieve reliable CIR estimations
- We propose to focus only the CIR part that relates to each desk to achieve generalizable estimation. By doing so, we design a ultra-low-power backscatter tag that enables automatic desk localization by mapping each tag to specific CIR components
- We design a CNN model for occupancy estimation
- We build the system with COTS UWB radios and customized PCB boards, and evaluate the system on two different rooms with different desk layouts

Ch1: Reliable Channel Impulse Response Estimations

- Hardware imperfection in bi-static UWB radios deployment
- Frame misalignment & Carrier Frequency Offset (CFO)
- Introduce noise to both amplitude and phase, making the CIR estimation less reliable

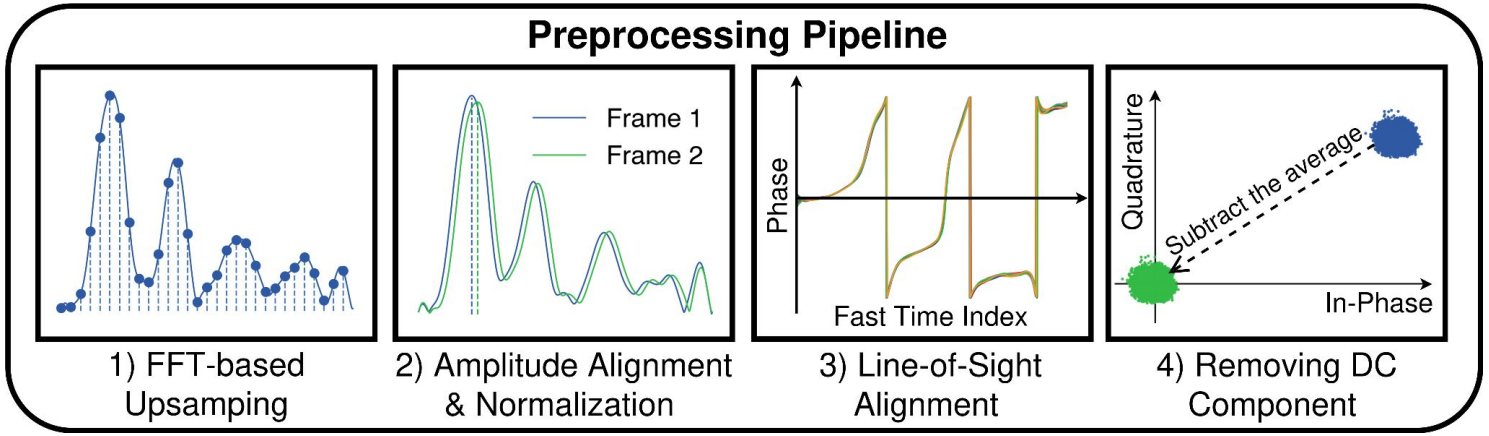






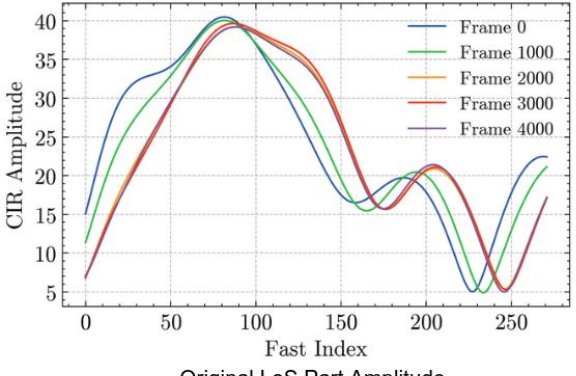
Signal Processing Pipeline to Calibrate the Imperfections

1. FFT Upsampling to increase the spatial resolution
2. Amplitude Normalization & Frame Alignment
   a. The UWB radios build a CIR estimation by accumulating preambles. We first normalize the amplitude based on the accumulation number
   b. Commonly, the APs will be deployed on the ceiling or wall. Therefore, we can safely assume that the LoS path between two AP is clear and stable

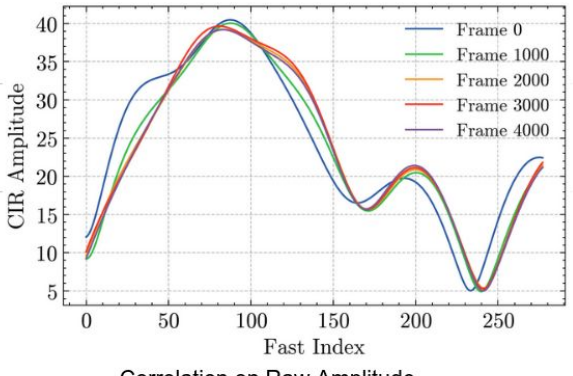


Cont'd: Frame Amplitude Alignment

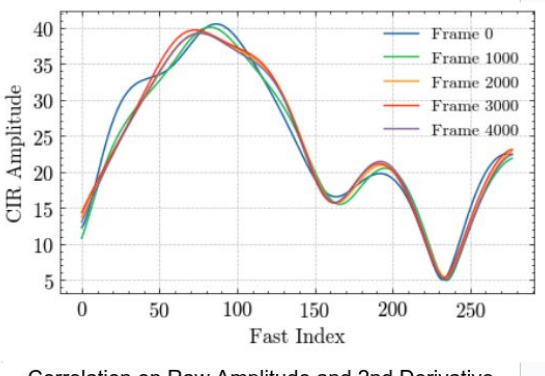
- We do correlation on the LoS part amplitude to determine the shift amount to a reference frame for amplitude alignment
- However, simply based on raw amplitude sometimes lead to suboptimal results. This is due to the potential merged peaks
- Therefore, we apply a second stage alignment based on the 2nd derivative of the signal, which is more sensitive to merged peaks



Original LoS Part Amplitude



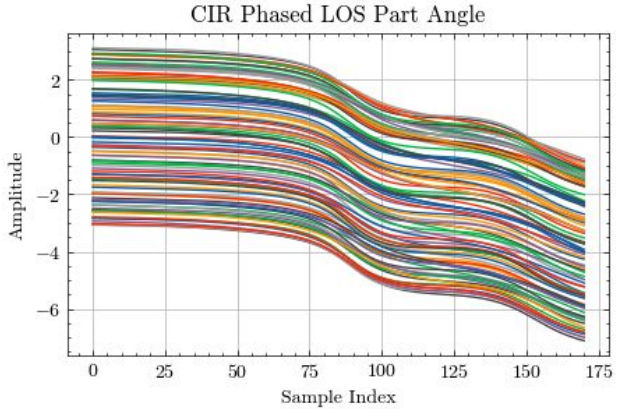
Correlation on Raw Amplitude

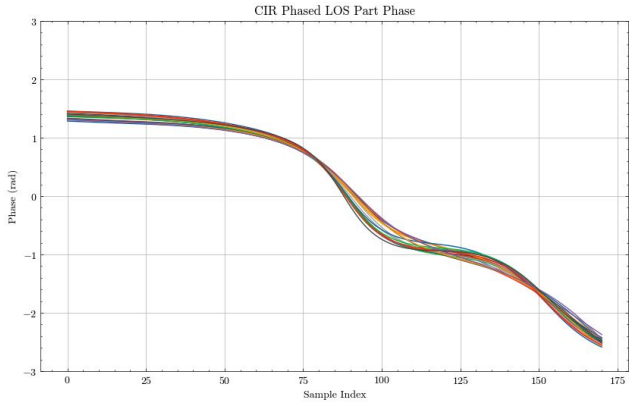


Correlation on Raw Amplitude and 2nd Derivative

Cont’d: Phase Alignment

- Similarly, we leverage the fact that LoS path is consistent across frames to correct the phase rotation caused by the CFO
- A “follow the leader” approach: Since the CFO applies the same phase rotation to all multipath components, we calibrated the CFO by estimating the phase rotation of the LoS path to a reference frame and compensating for this rotation across all CIR components.



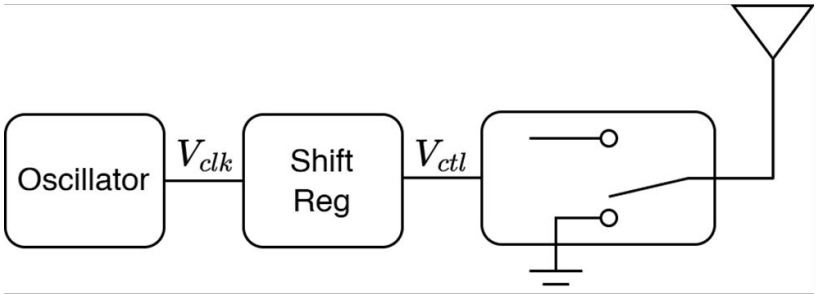


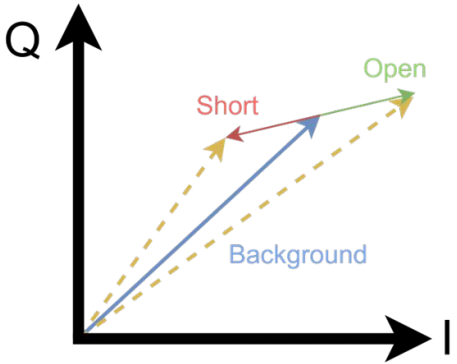
Ch2: Occupancy Sensing under Varying Room Geometry

- CIR varies significantly across different rooms and even the same room with different desk layouts
- The goal is to achieve generalizable desk-level sensing without requiring extensive per-room/per-layout data collection and finetuning
- We propose to focus on only the CIR components that correspond to each desk, which is a geometry-aware approach

Mapping CIR components with desks at scale

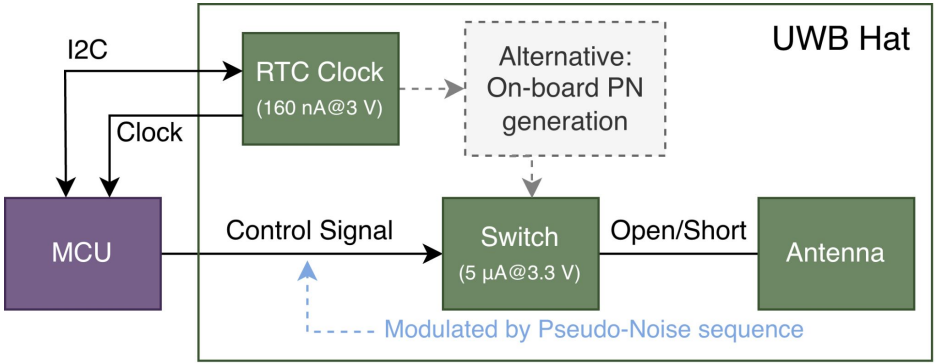
- To do so, we design an ultra-low-power backscatter tag
- By attaching such a tag to each desk, which reflects UWB signals with a unique pseudo-noise (PN) sequence, we can detect the existence of such a pattern in CIR estimations
- By finding the which part of the CIR has such pattern, we can then map that part with a corresponding tag, and therefore, a desk

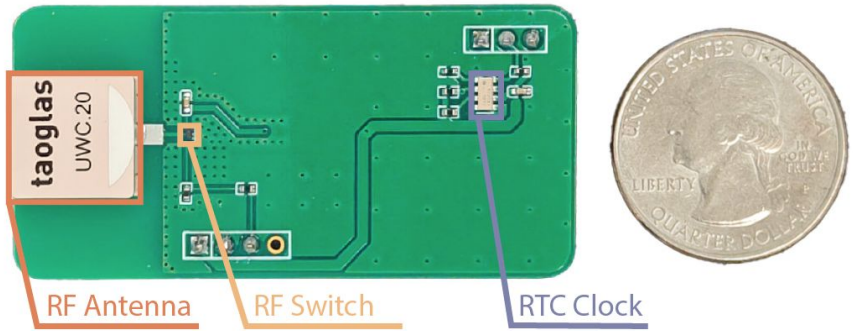




UWB Backscattered Tag

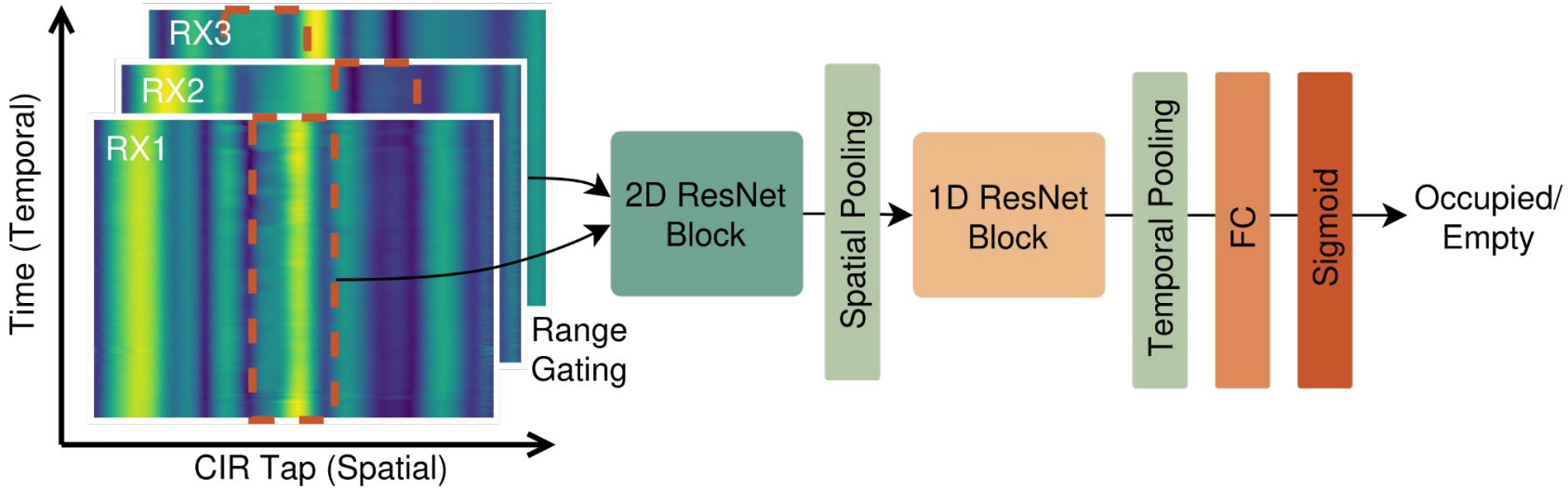
- RTC clock: create steady clock signal
- A SP2T switch, direct the RF signal to either a short or open port
  - Both re-radiate the signal, but with 180° phase difference
- MCU: generate a Pseudo Noise code for tag to embed
  - Kasami Code: Very high auto-correlation and low cross-correlation



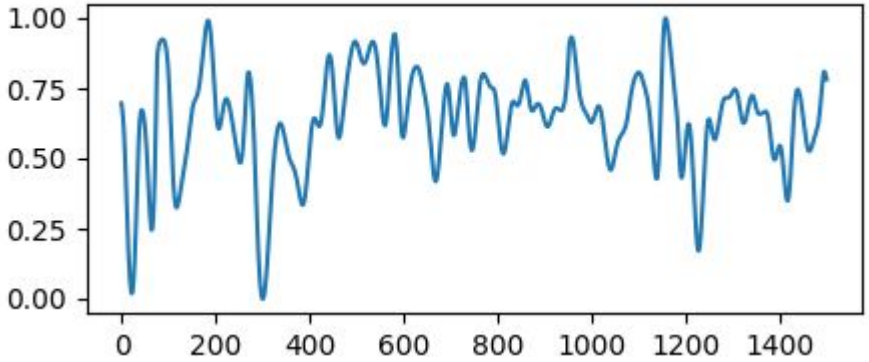


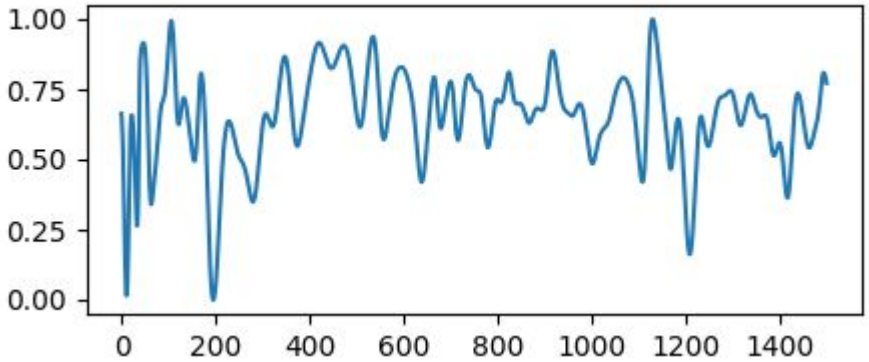
Occupancy Prediction Model

- First range-gating the corresponding CIR components
- Feed into a 2D ResNet block to capture both spatial and temporal information



Data Augmentation:





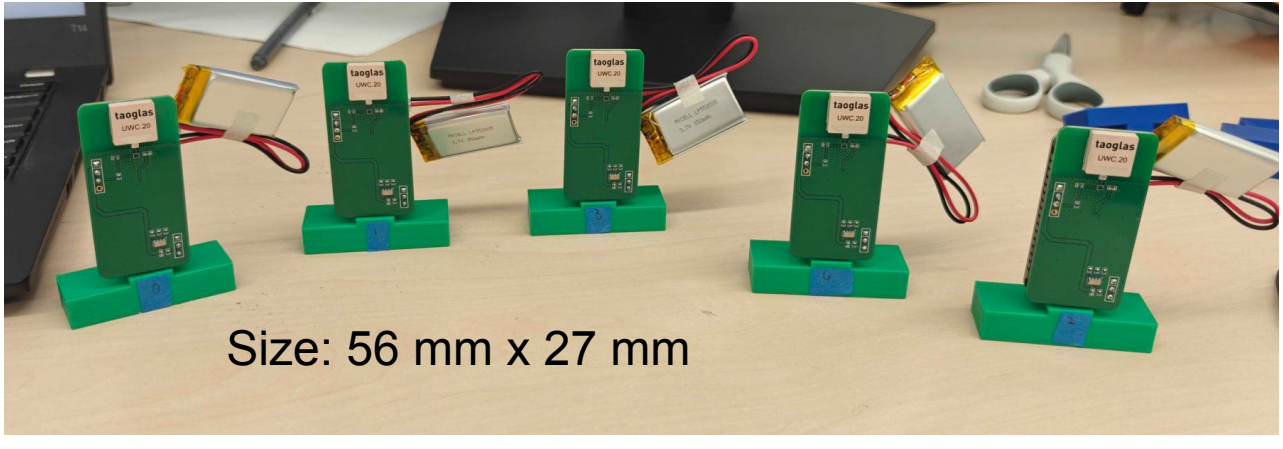
- Gaussian noise
- Time warping: to simulate some speed variance
- Random range center shifts during range-gating

Implementation - UWB Node

- UWB module: Qorvo DMW3001CDK, Channel 9 (7.9GHz with 500MHz Bandwidth)
- Use raspberry pi to control and streaming data
- Heavy firmware optimization to support stable estimation rate up to 1024Hz

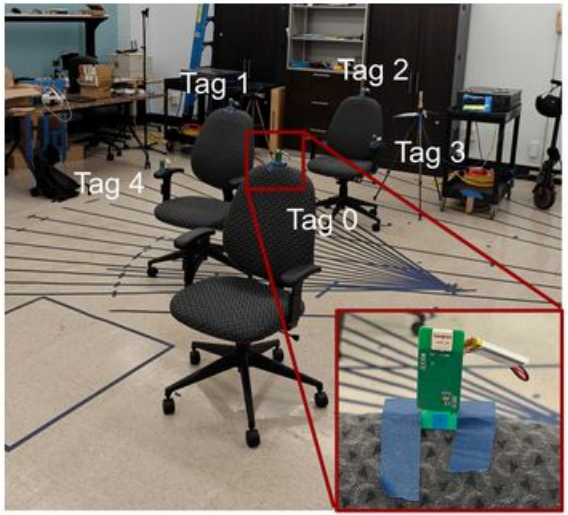
Implementation - Tag

Part	Cost [$]		Quiescent Power		
	@1	@1000	Current [µA]	Volt. [V]	Power [µW]
Taoglas UWC.20 Antenna	3.89	1.94	*Passive (no quiescent power)*		
SKY59608-711LF Switch	0.68	0.32	15.00	3.3	49.50
RTC RV-3032-C7 Clock	3.18	1.73	0.16	3.0	0.48

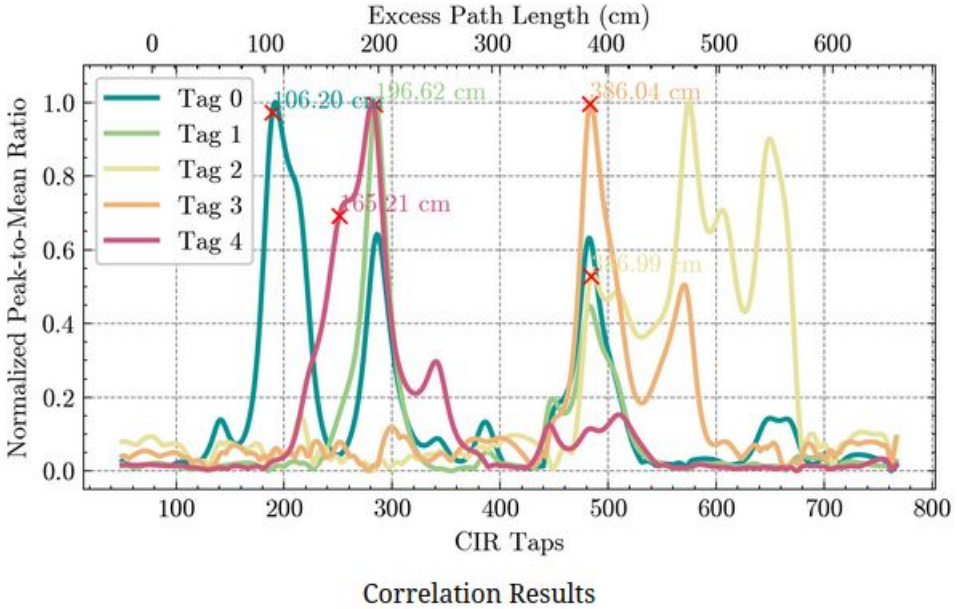


Evaluation: Localization Benchmarking

- Localize 5 tags simultaneously, with error <10 cm
- We apply a derivative-based peak search algorithm to find the earliest peak with a normalized amplitude >0.3

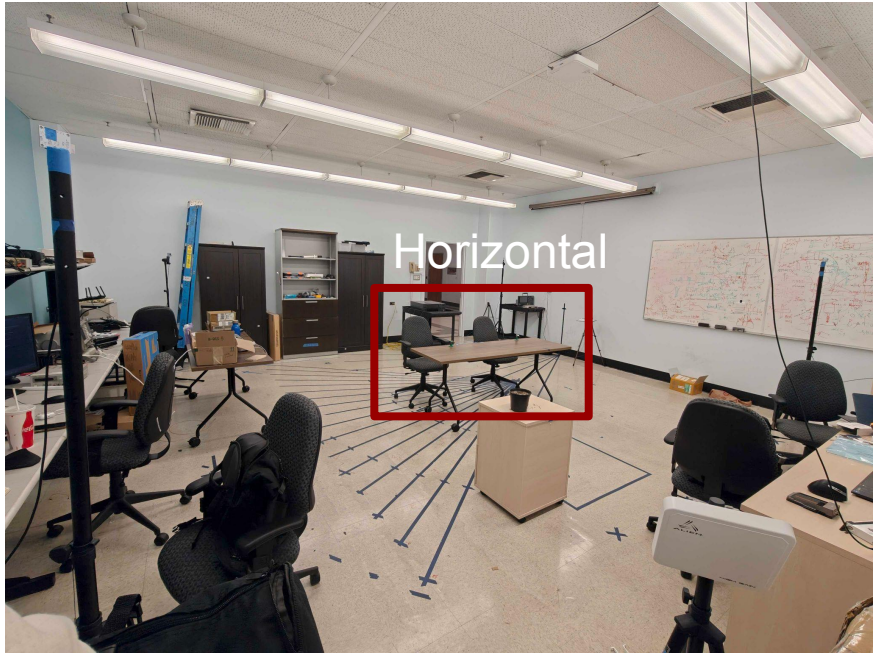


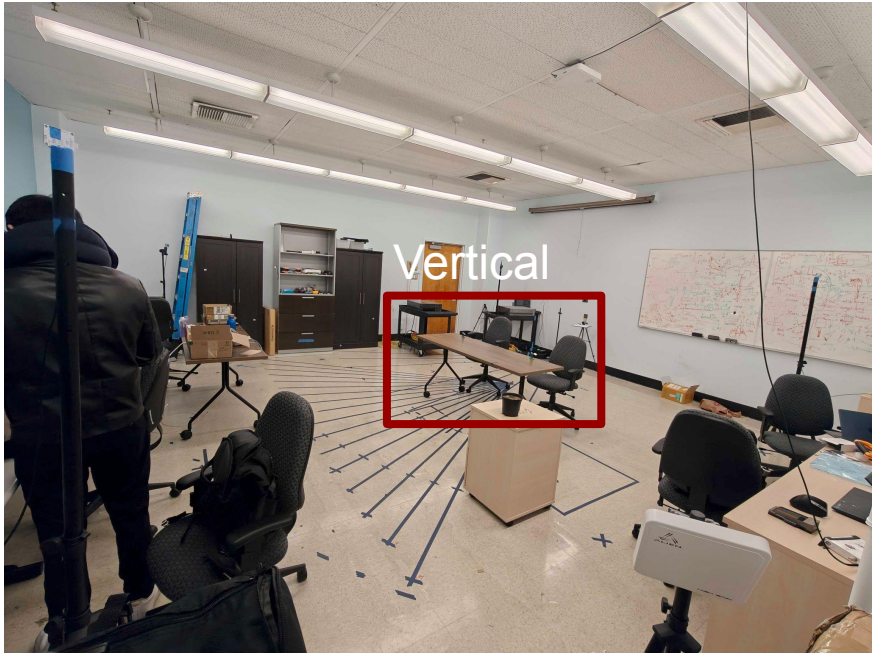
Tag Deployment Setup



Correlation Results

Evaluation: Test on unseen desk layout



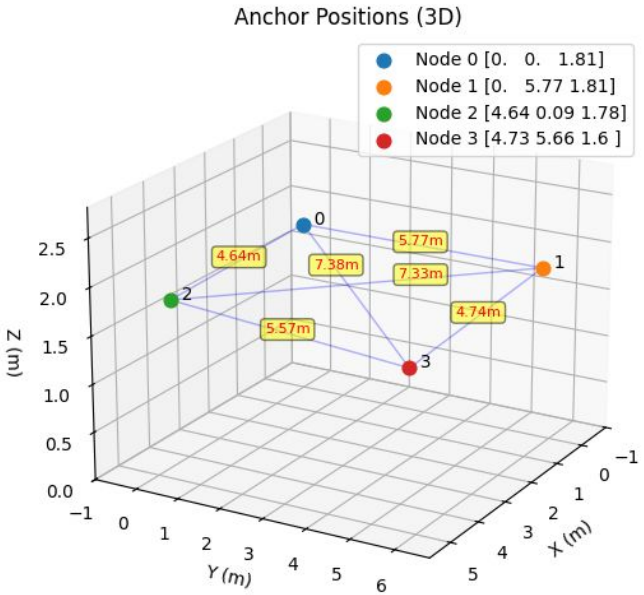


Occupy Seat 1 and Seat 2 separately

Empty with static environment, moving around, standing aside

Range-gated compared with the full-range CIR baseline

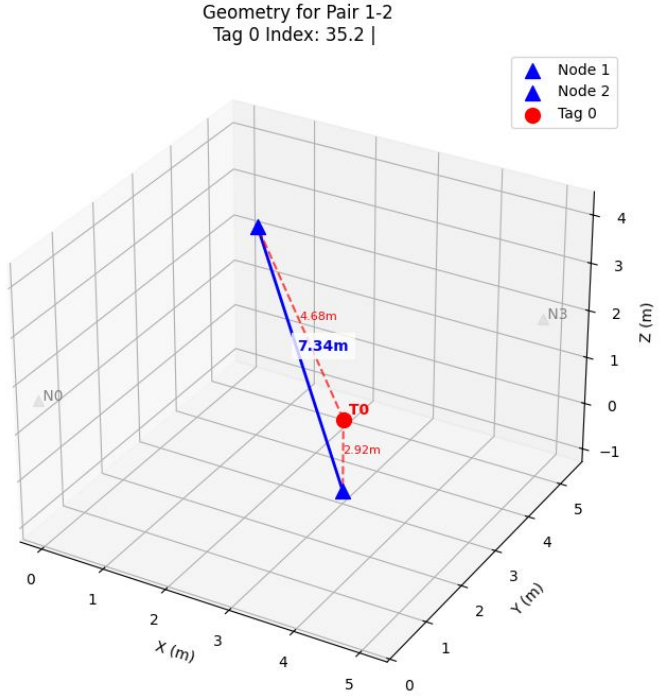
- Test accuracy: 79.17% v.s. 66.67%
- Train accuray: 86.11% v.s. 97.66%



- Current tripod stand is relatively low (1.6m to 1.8m)
- When people moving around, the movement create a lot variance to the LoS path -> affect the quality of the following alignment and postprocessing

Sitting human can also disturb the LoS

- The desk is around 1m
- For Node1 to Node 2 (Diagonal) human sitting on the desk corresponds an excess path length of only 26 cm (Very close to the LoS path)



Future direction: experiment with higher stands

- This is more similar to the real deployment where APs typically mounted on the ceiling or on the wall

Future Direction:

- Collect more data with more diverse room layouts and desk layouts
- Explore the same approach with radar kits
- Combine current model training approach with more advanced techniques such as domain adaptation and self-supervised learning

Work

- Firmware optimization to support high estimation rate and multi-node sensing
- PCB board design and fabrication
- Arduino code for MCU to configure RTC clock and provide Pseudo-Noise coded control signal
- Signal processing pipeline development for robust CIR estimation
- Tag localization algorithm development
- Data collection
- CNN modeling and training