Contactless Sensing

Department of Computer Science and Engineering

INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

Part III: mmWave Sensing

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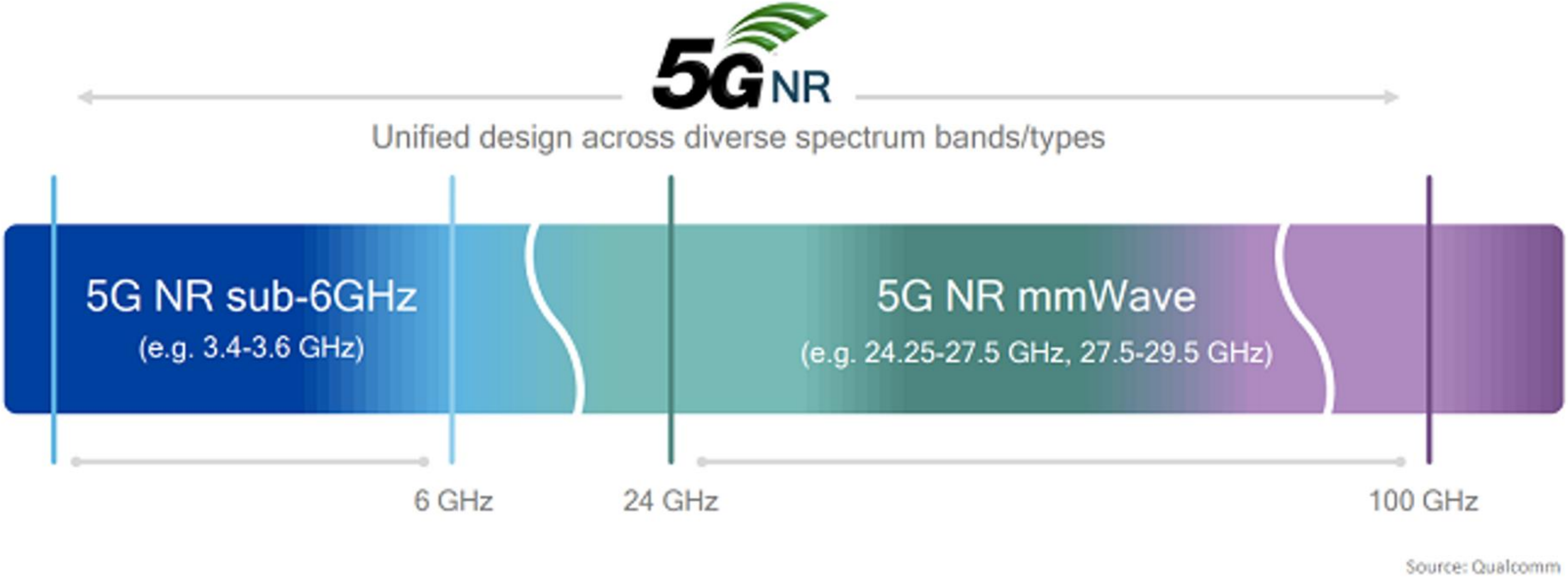
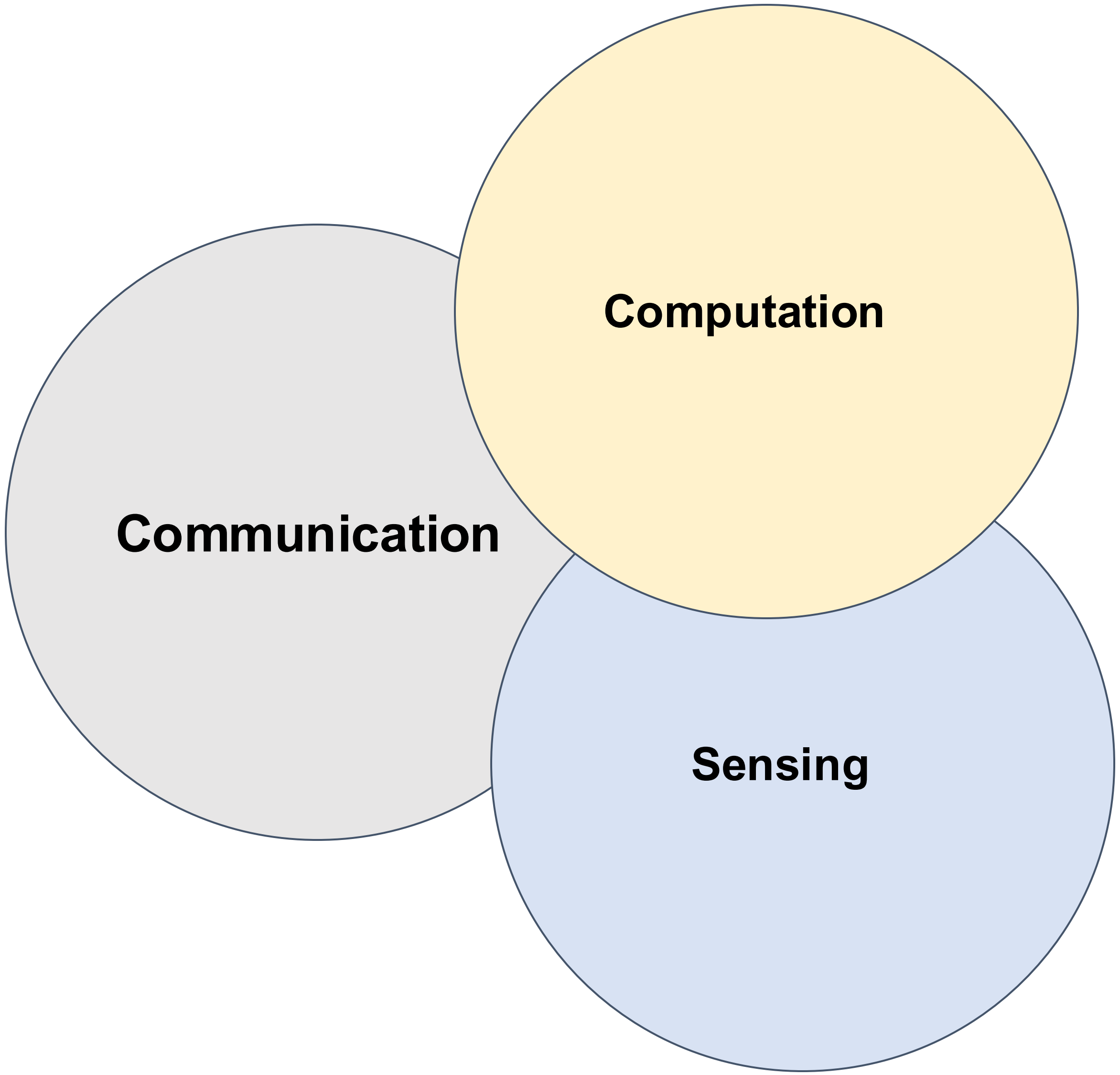
Thanks to Argha Sen and Debjit Chatterjee for helping with the slides!

5G New Radio (NR)

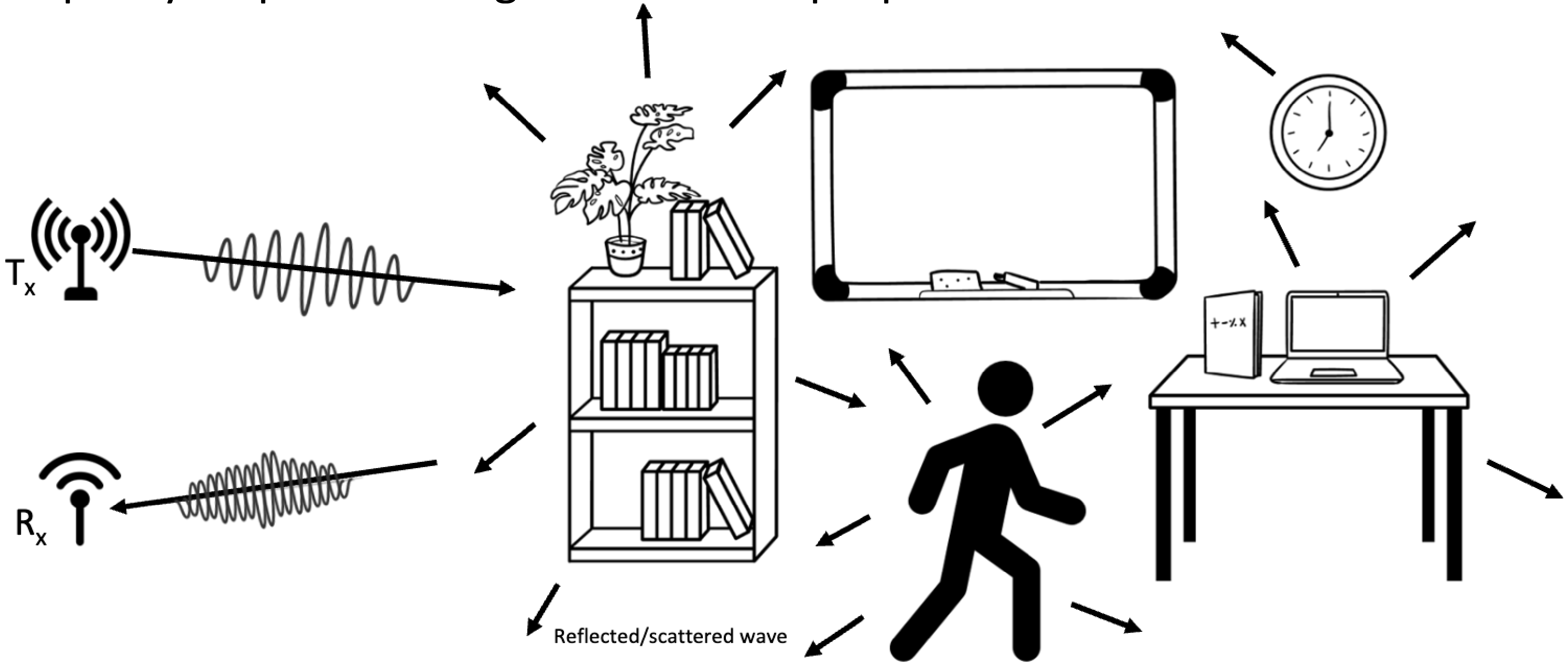


Ubiquitous Computing over 5G



Background: How Sensing Works

- Signals gets reflected from human subjects and other objects in the periphery: Explore the signal reflection properties



Human Activity Recognition

Source	Sensor	Feature	Inference
Gesture Vital Signs Presence & movement Location		• **Signal Processing:** AoA, Point-cloud, RSSI/SINR • **Deep Learning** based feature extraction n/w	• Speech recognition • Indoor positioning • Breathing monitoring • Facial expression recognition • Gesture recognition • Localization/tracking

Various Sensing Modalities

Signal	Frequency	Key properties signifying applicability
Acoustics	20 Hz - 20 kHz(audible) >20 kHz	Affected by acoustic interference in environment
UWB	3.1 GHz to 10.6 GHz	Interference with sub 6 GHz Communicating Devices
Wifi	2.4 GHz/ 5 GHz	Low Range resolution, less accuracy with CSI
mmWave	30–300 GHz	Various commercial devices. Prominent technology of the near future
Bluetooth	2.4GHz	Low Resolution
LoRA	169 MHz, 433 MHz, 868 MHz and 915 MHz	Long range sensing but not apt for indoor

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A Vast Literature on RF Sensing

Wifi

- Presence Detection
- Counting crowd
- Breathing monitoring
- Heart rate monitoring
- Hand gesture recognition
- Fire detection
- localization/tracking
- Fall detection
- Smoking detection
- Mouth movement
- Keystroke Recognition
- Traffic Monitoring
- Driver Fatigue Detection
- LOS detection
- Metal detection
- Finger Gesture Recognition
- Multi-User Gesture Recognition
- Human Identification

Acoustics

- Breathing monitoring
- Heart rate monitoring
- Eyelid movement
- Hand gesture recognition

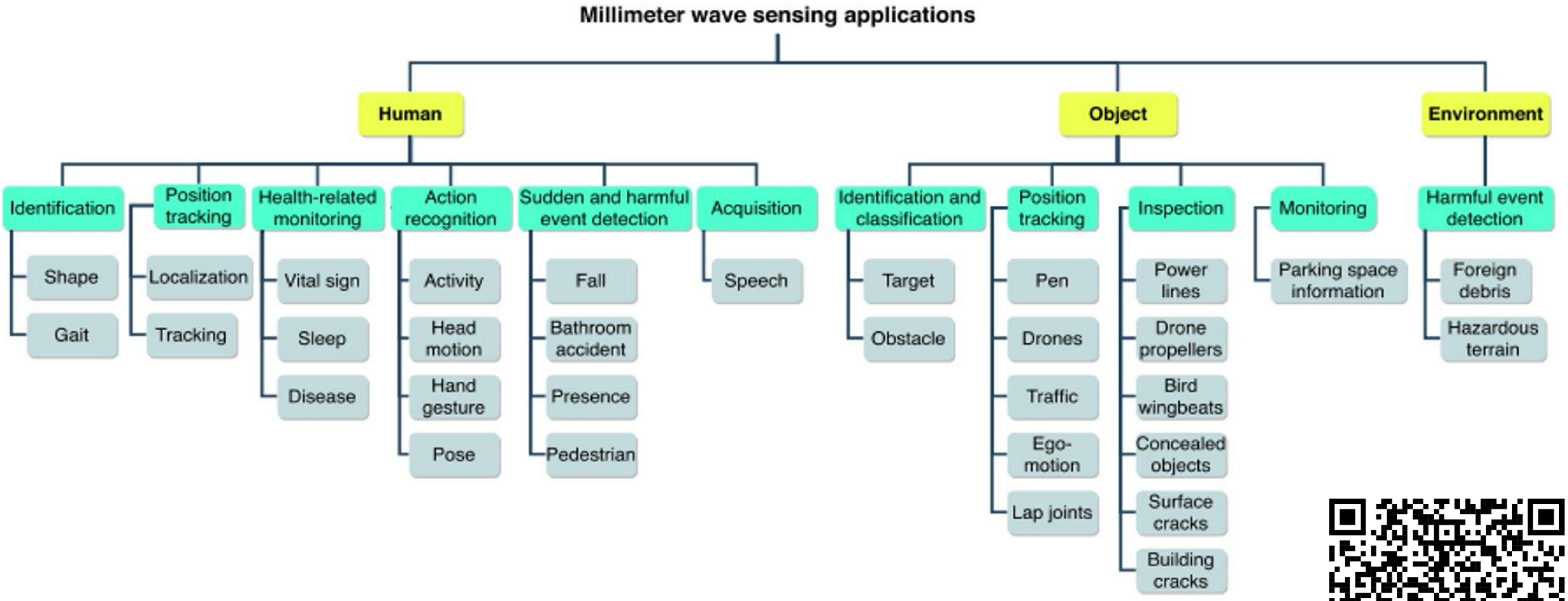
UWB

- Heartbeat monitoring
- Gesture recognition
- Speech recognition
- Respiration Monitoring
- Eyelid movement
- Gait Abnormality Detection

mmWave

- Temperature Monitoring
- Speech recognition
- Indoor positioning
- Multi-user breathing monitoring
- Facial expression recognition
- Gesture recognition
- Localization/tracking
- Fall detection
- Gait identification
- Emotion detection
- Heart beat monitoring
- Parking space monitoring
- Presence detection
- Parking space monitoring
- Gas monitoring

mmWave Sensing – A Vast Literature



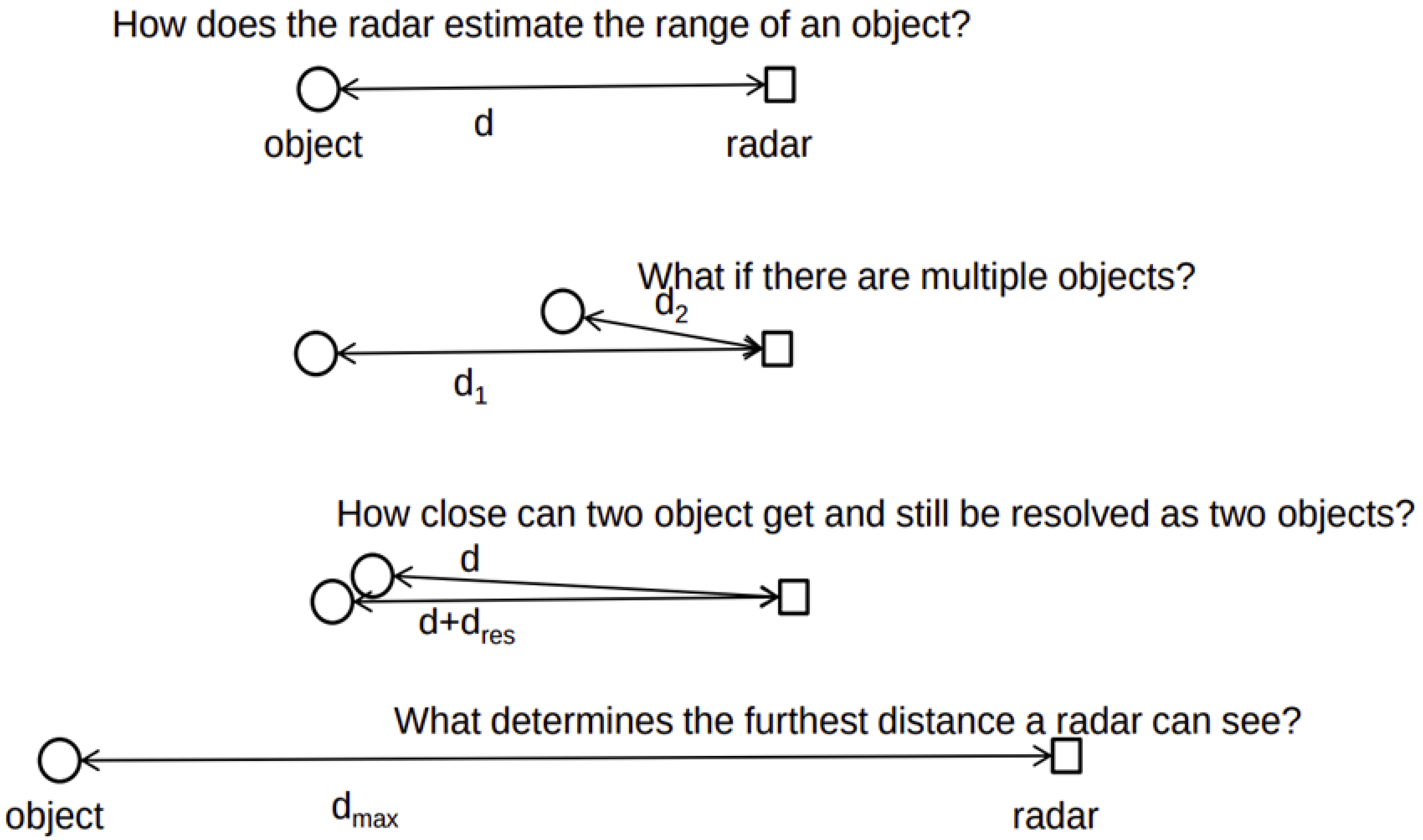
mmWave Sensing

- mmWave sensing follows the radar principles

- Uses various modulation schemes widely used in commercial radars
    - Phase modulation: Use the phase difference to capture the AoA
    - Continuous Wave modulation: Uses a constant frequency carrier; cannot measure range as the carrier signal is unmodulated
    - Frequency Modulated Continuous Wave (FMCW)

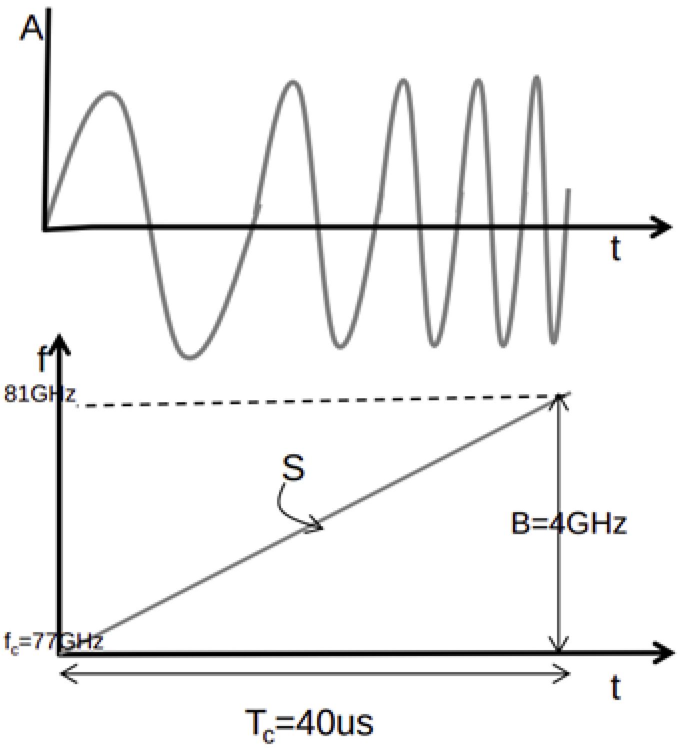
FMCW Radars

- The basic objectives of a radar are the followings:



FMCW Radars

- FMCW radar transmits **chirps**
- A chirp is characterized by a fc, B and T_c.
- The Slope (S) defines the rate at which the chirp ramps up.



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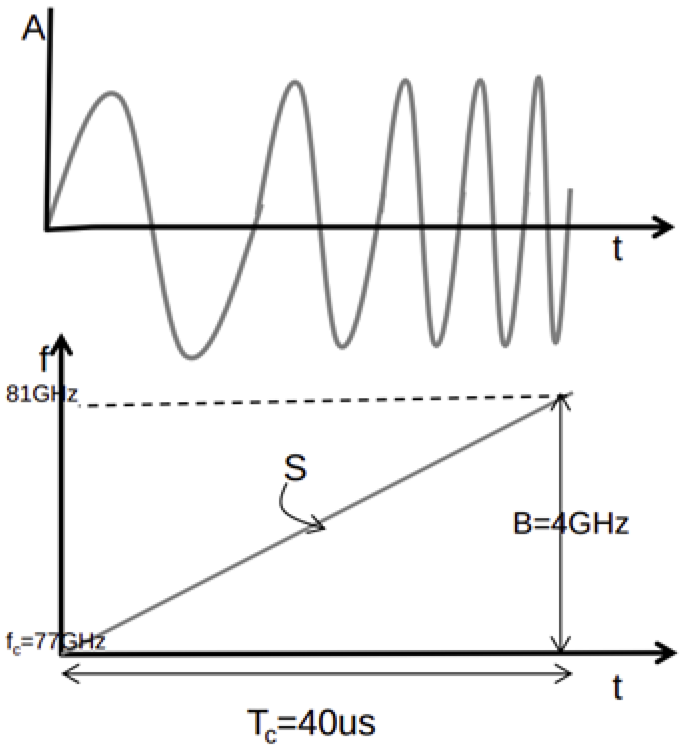
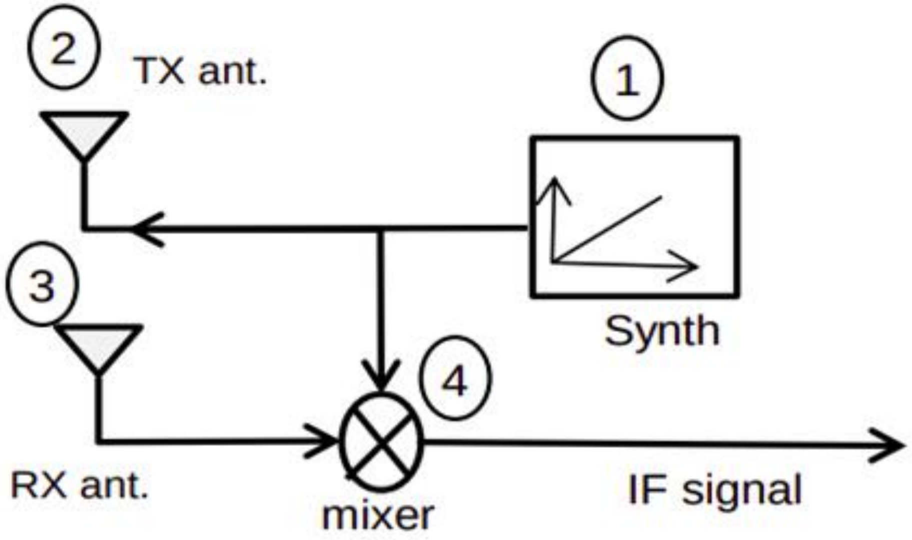




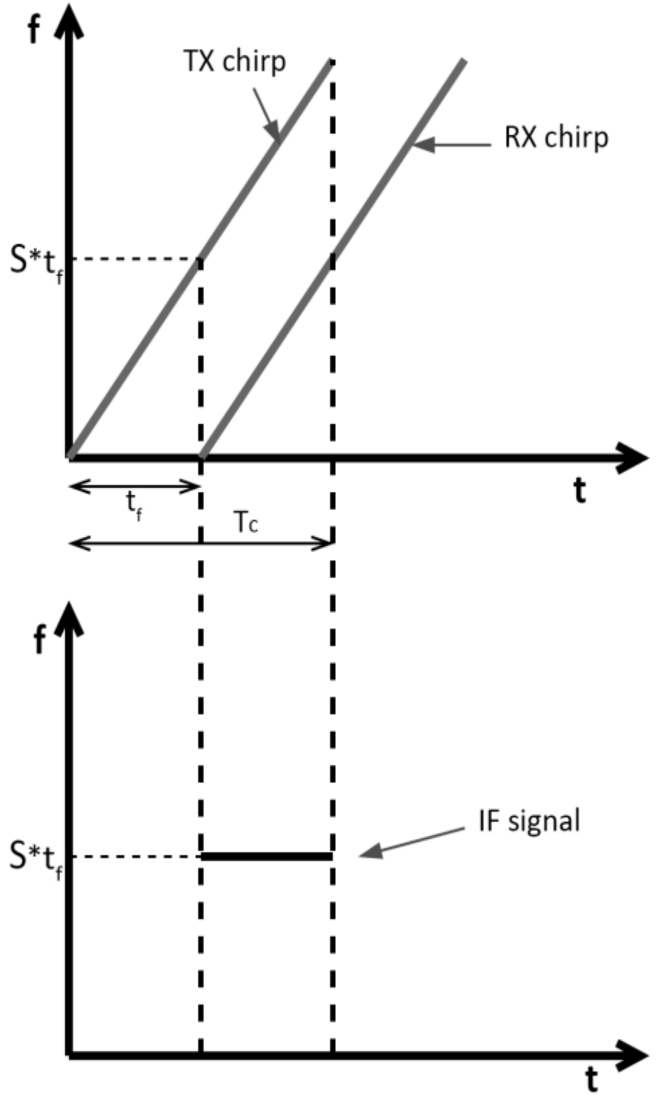
TX Signal: $x_1 = \sin(w_1 t + \varphi_1)$

RX Signal: $x_2 = \sin(w_2 t + \varphi_2)$

$$x_{out} = \sin[(w_1 - w_2)t + (\varphi_1 - \varphi_2)]$$

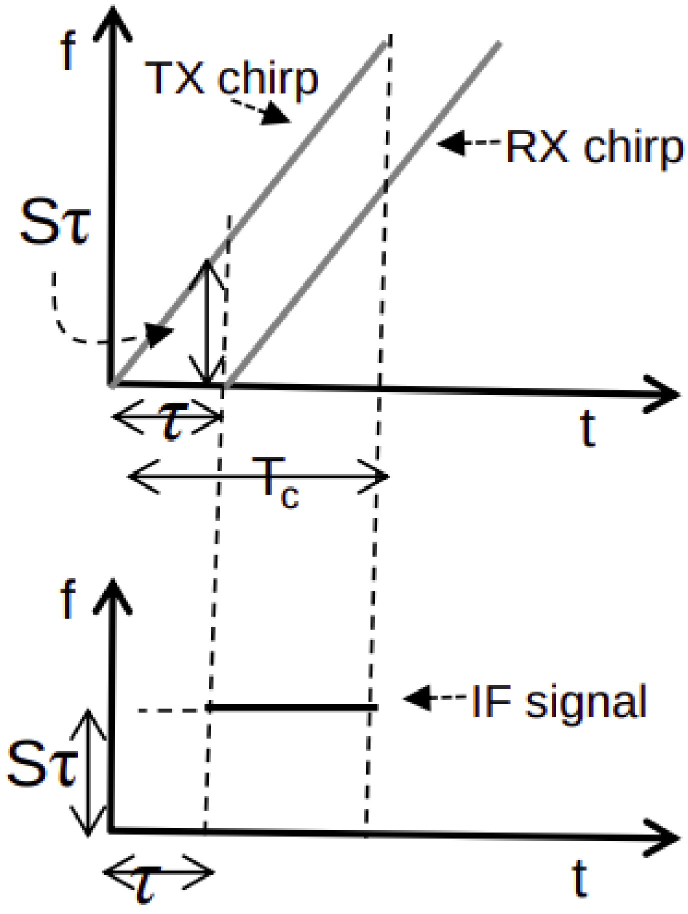
FMCW Radar: The IF Signal

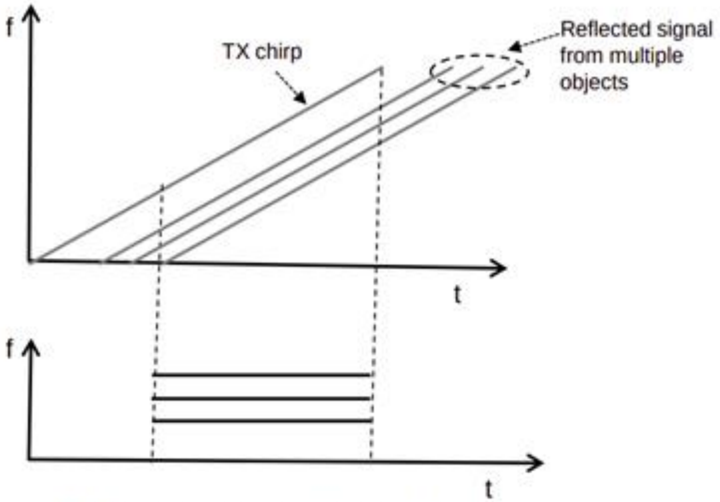
- The Rx is the replica of the Tx shifted in time $t_f = 2d/c$
- Tx and Rx has the same linear modulation, the difference is a constant tone
  - Equals to the round trip delay multiplied by the slope of the signal
  - Slope $S = B/T_c$, B is the bandwidth
  - The resultant frequency is called **the intermediate frequency (IF)**



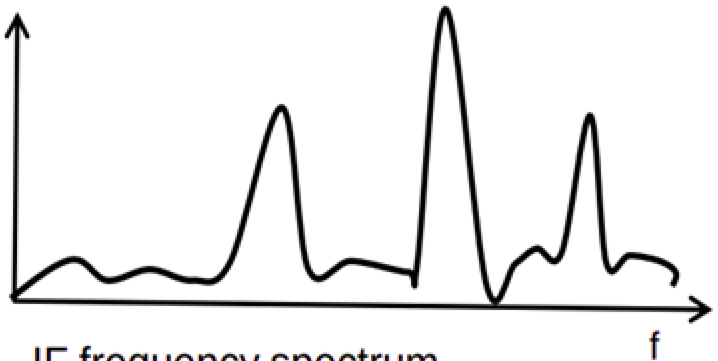
FMCW Radar: The IF Signal

- The frequency difference of the TX-chirp and RX-chirp.
- Object in front of the radar produces an IF signal with a constant frequency tone.
- The frequency of this tone is $f_{IF} = S.\tau = S.2d/c$
- $\tau = 2d/c$ is the round-trip time





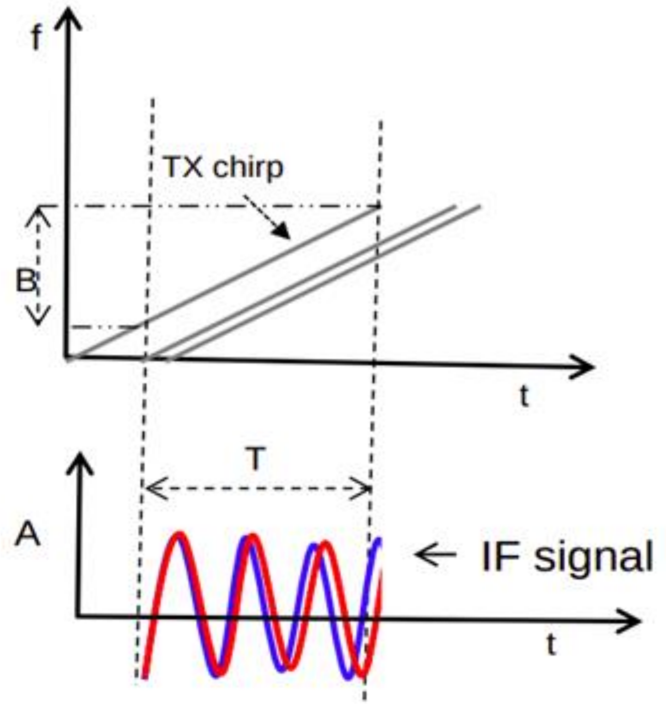
Multiple tones in the IF signal

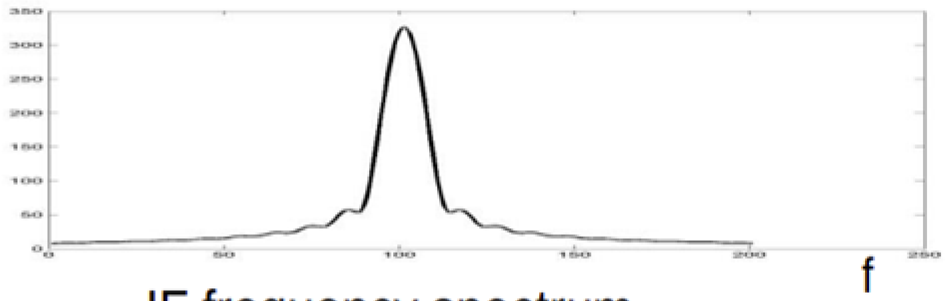


IF frequency spectrum

FMCW Radar: Range Resolution

- **Range Resolution**: Ability to resolve two closely spaced objects.
- When the two objects are too close that they show up as a single peak in the frequency spectrum.
  - The two objects can be resolved by increasing the length of the IF signal.

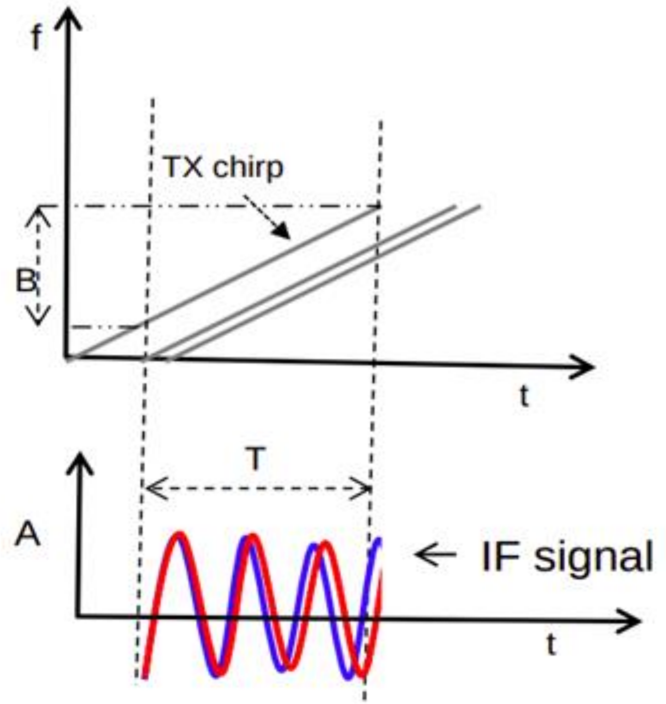


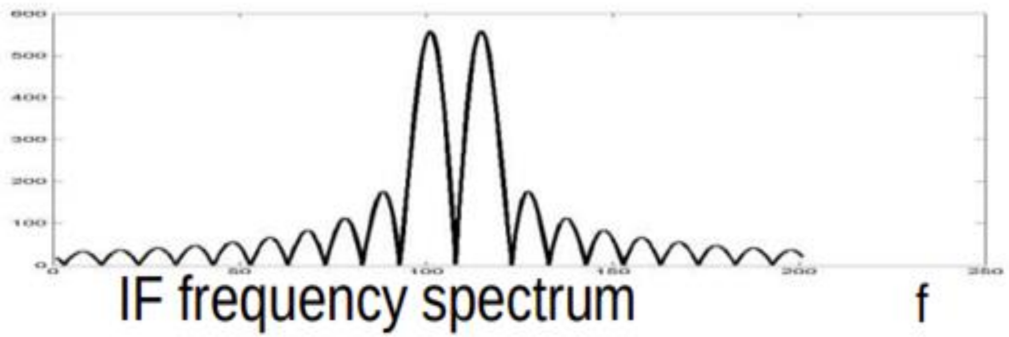


IF frequency spectrum

FMCW Radar: Range Resolution

- **Range Resolution**: Ability to resolve two closely spaced objects.
- When the two objects are too close that they show up as a single peak in the frequency spectrum.
- This also proportionally increases the bandwidth (as we need to increase the chirp duration)!
- Thus increasing the bandwidth provides better resolution



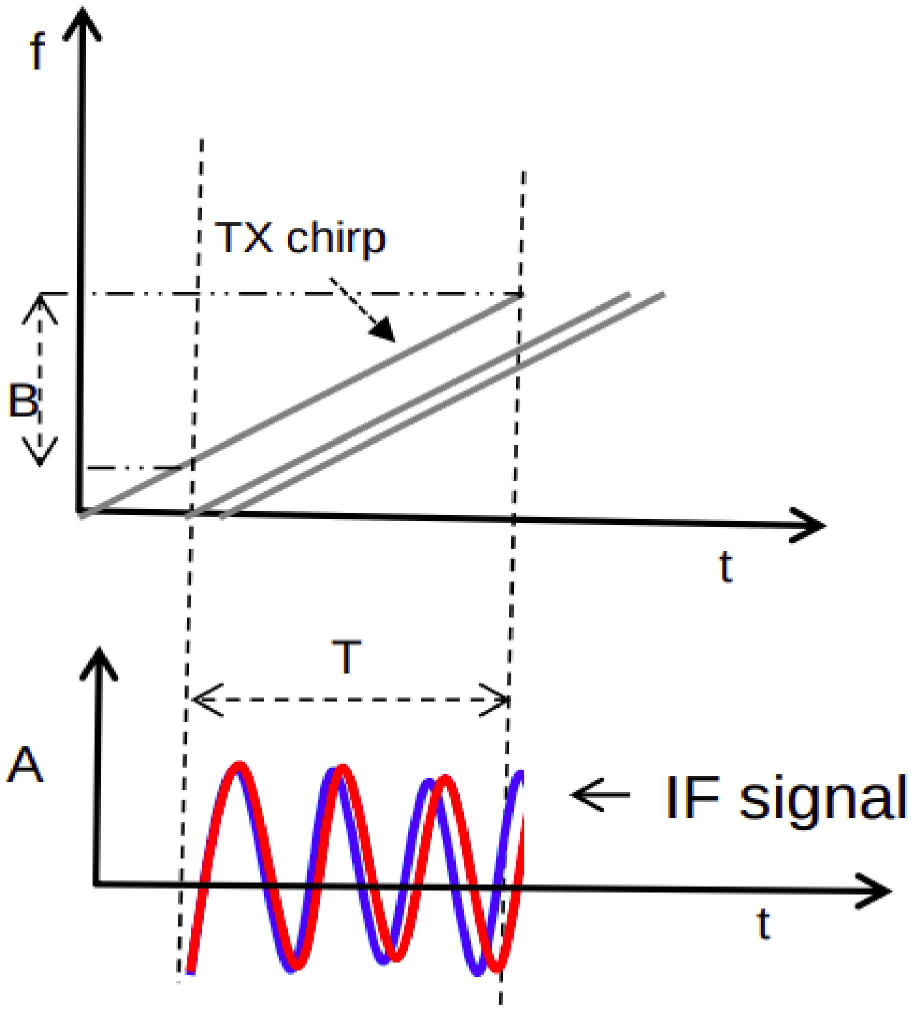


FMCW Radar: Range Resolution

Range Resolution: Ability to resolve two closely

To resolve two different tones in the frequency spectrum, they must be spaced more than 1/T, where T is the window duration. In this case, T equals to T_c.

- Increasing the length of the IF signal?
- This also proportionally increases the bandwidth!
- Thus intuitively: Greater the Bandwidth => better the resolution.

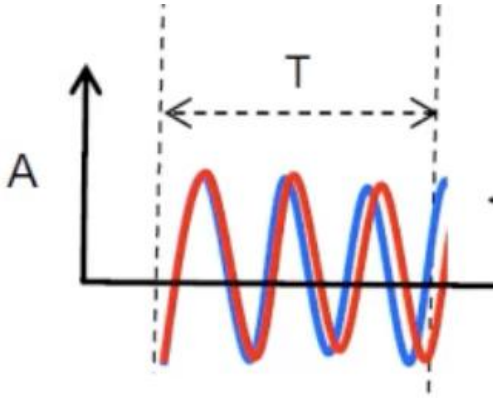


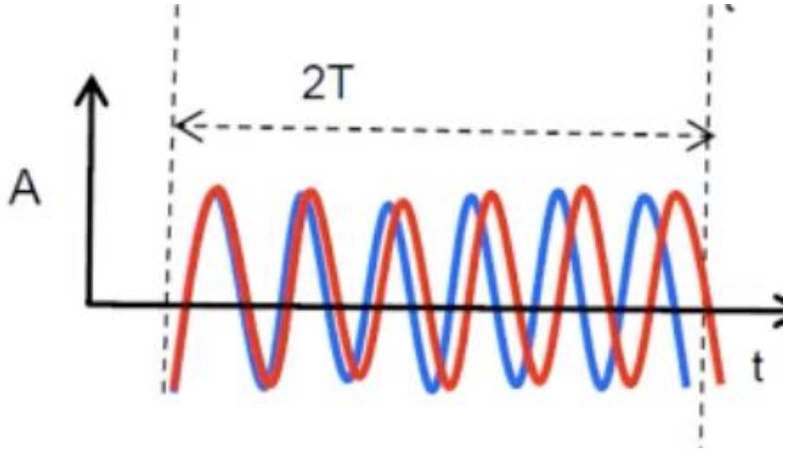
An Important Observation from FFT

- **To resolve two different tones in the frequency spectrum, they must be spaced more than 1/T, where T is the window duration – Why?**

- We often perform the Fourier transform on finite window (duration T), as we cannot analyze an infinitely long signal

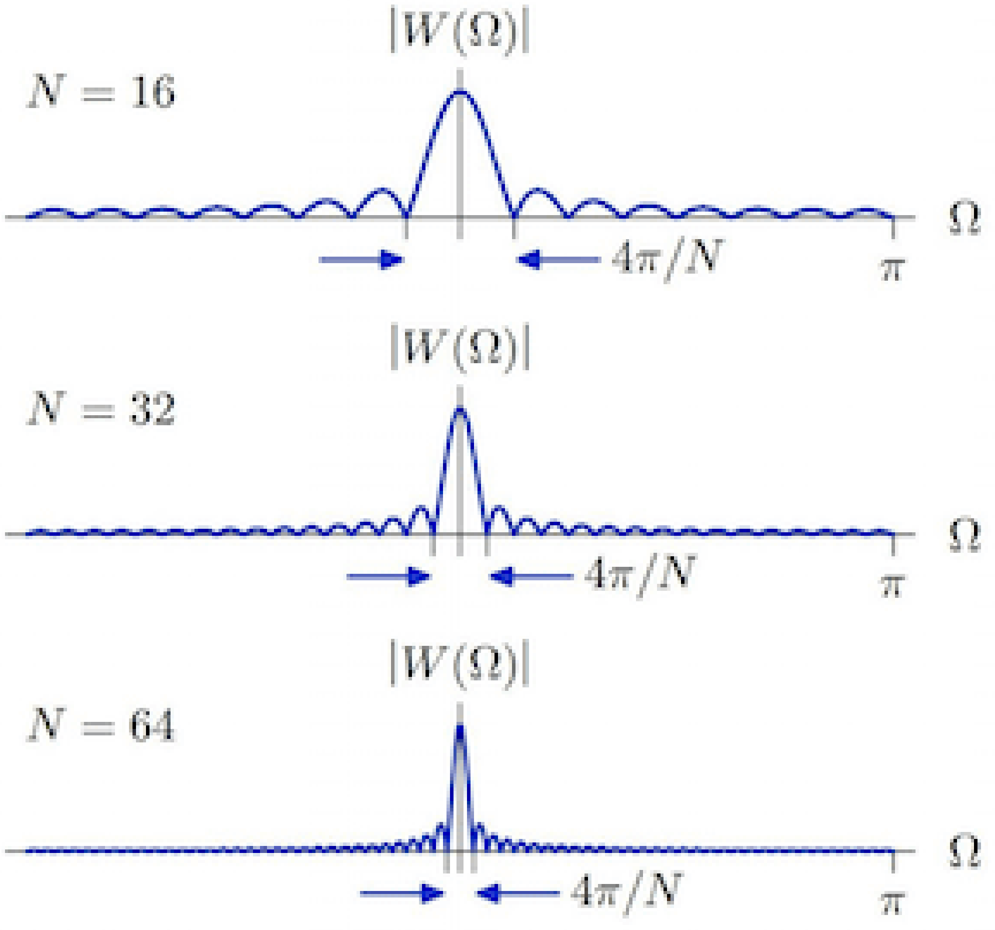
- **Frequency Resolution:** The smallest frequency difference that can be distinguished in the Fourier-transformed signal





An Important Observation from FFT

- **Frequency Resolution:** The smallest frequency difference that can be distinguished in the Fourier-transformed signal
  - The sine waves or tones in the signal are transformed into peaks in the frequency domain.
  - Each tone, after the Fourier transform, results in a spread of energy across several frequency bins due to the finite window.
  - For two tones to be resolved, the distance between their frequencies must be larger than the spread of each tone, which is approximately 1/T

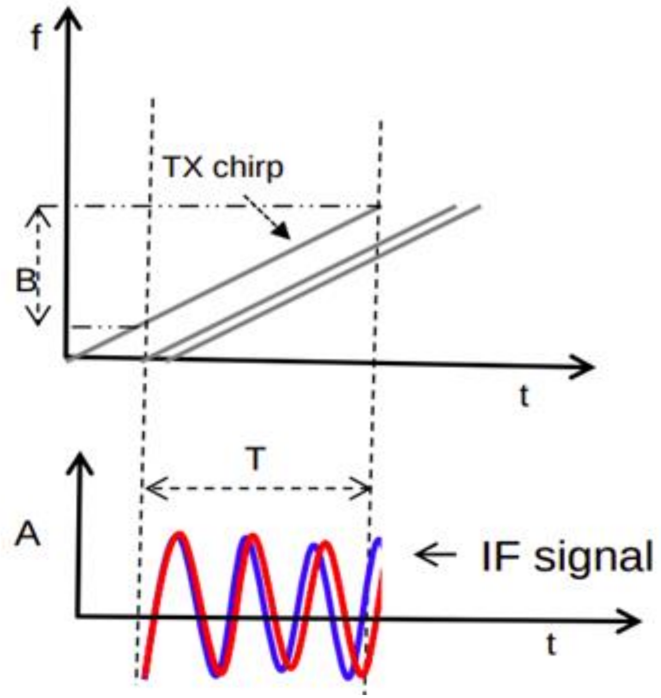


FMCW Radar: Range Resolution

To resolve two different tones in the frequency spectrum, they must be spaced more than 1/T, where T is the window duration. In this case, T equals to T_c.

The minimum range resolution can be computed as:

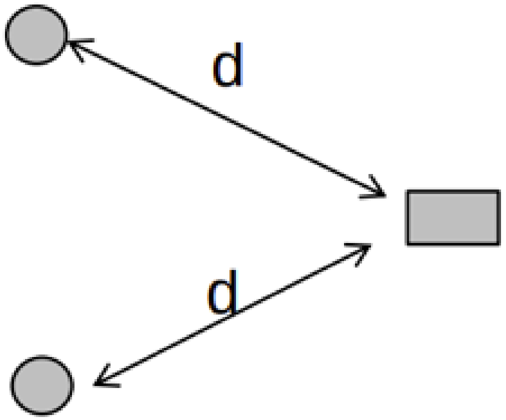
$$\Delta f > \frac{1}{T_c} \Rightarrow \frac{S2\Delta d}{c} > \frac{1}{T_c} \Rightarrow \Delta d > \frac{c}{2ST_c} \Rightarrow \frac{c}{2B} \quad \text{(since } B=ST_c\text{)}$$



Some typical numbers	
Bandwidth	Range Resolution
4GHz	3.75cm
2GHz	7.5cm
1GHz	15cm
600MHz	25cm

Equidistance Objects

- Two objects are equidistant from the radar. How will the range-FFT look like?



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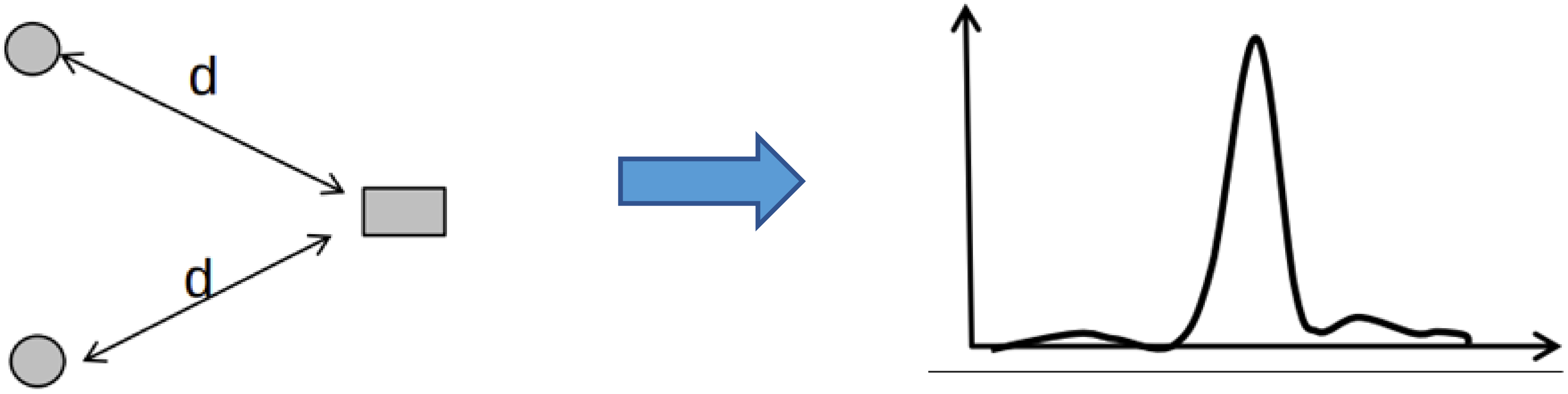

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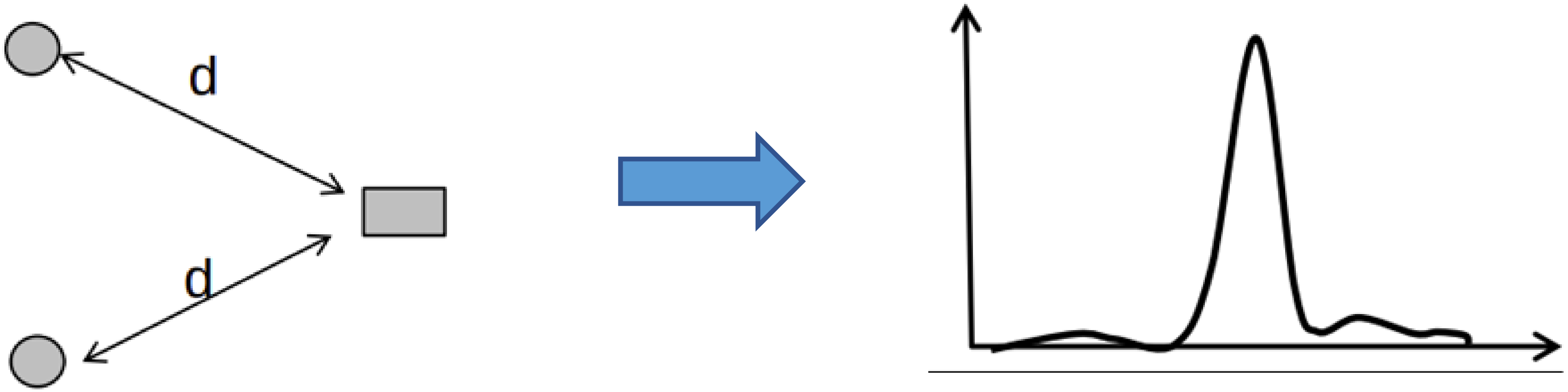

How do we separate these two objects?

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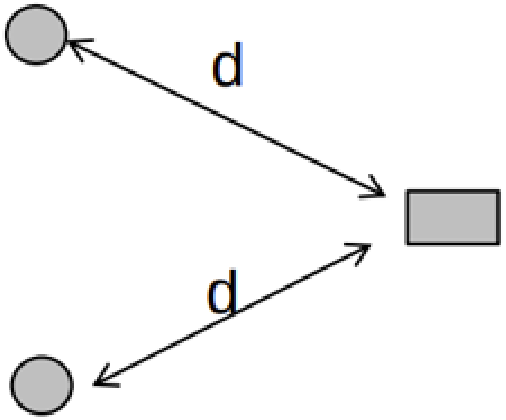
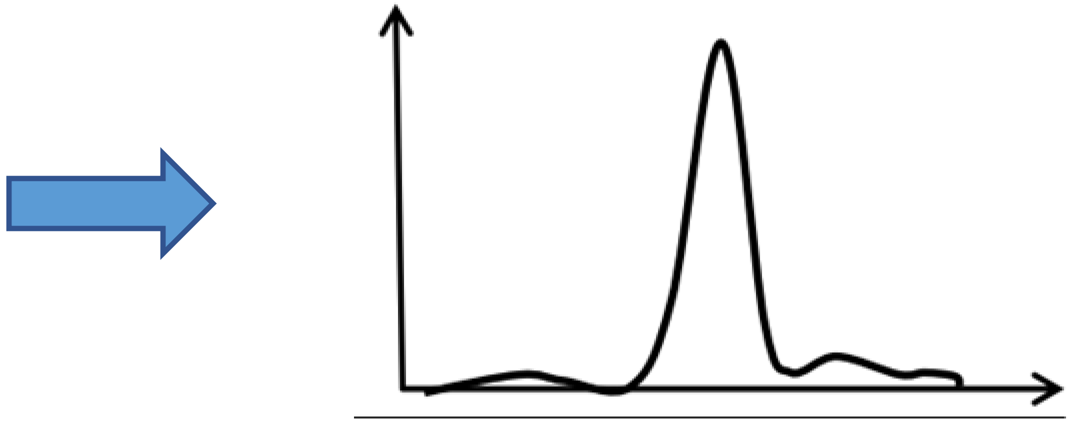


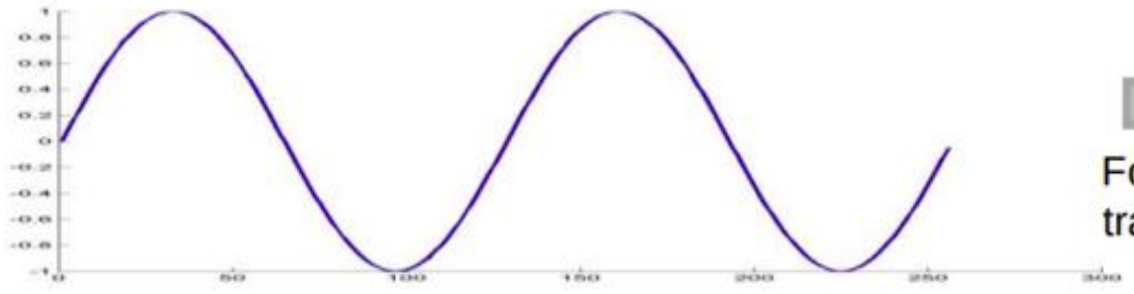


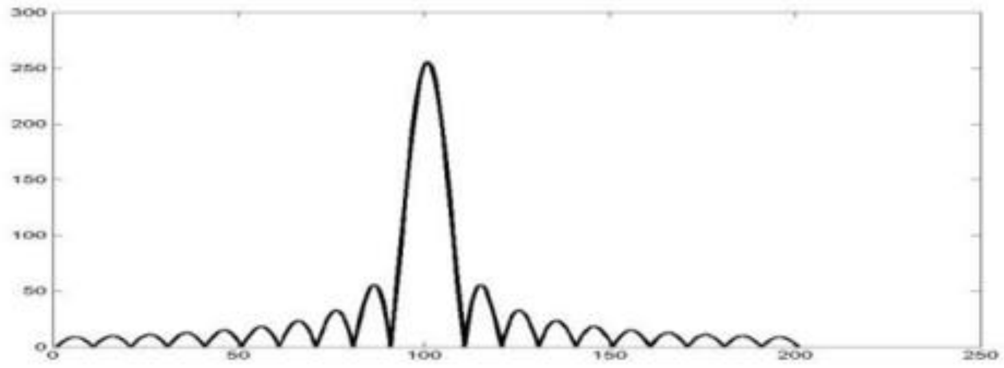
How do we separate these two objects?

The phase information helps!

FMCW Radar: Phase of the IF Signal

- Fourier Transforms: A sinusoid in the time domain produces a peak in the frequency domain.
- The signal in the Frequency domain is complex (i.e., each value is a phasor with an amplitude and a phase)





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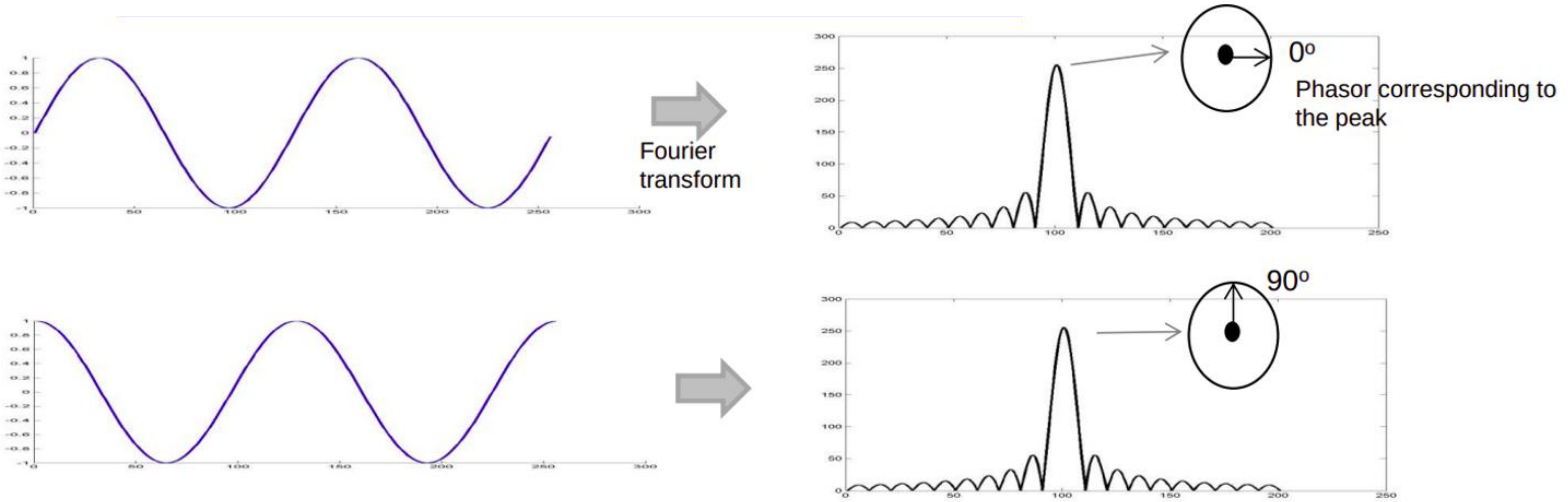

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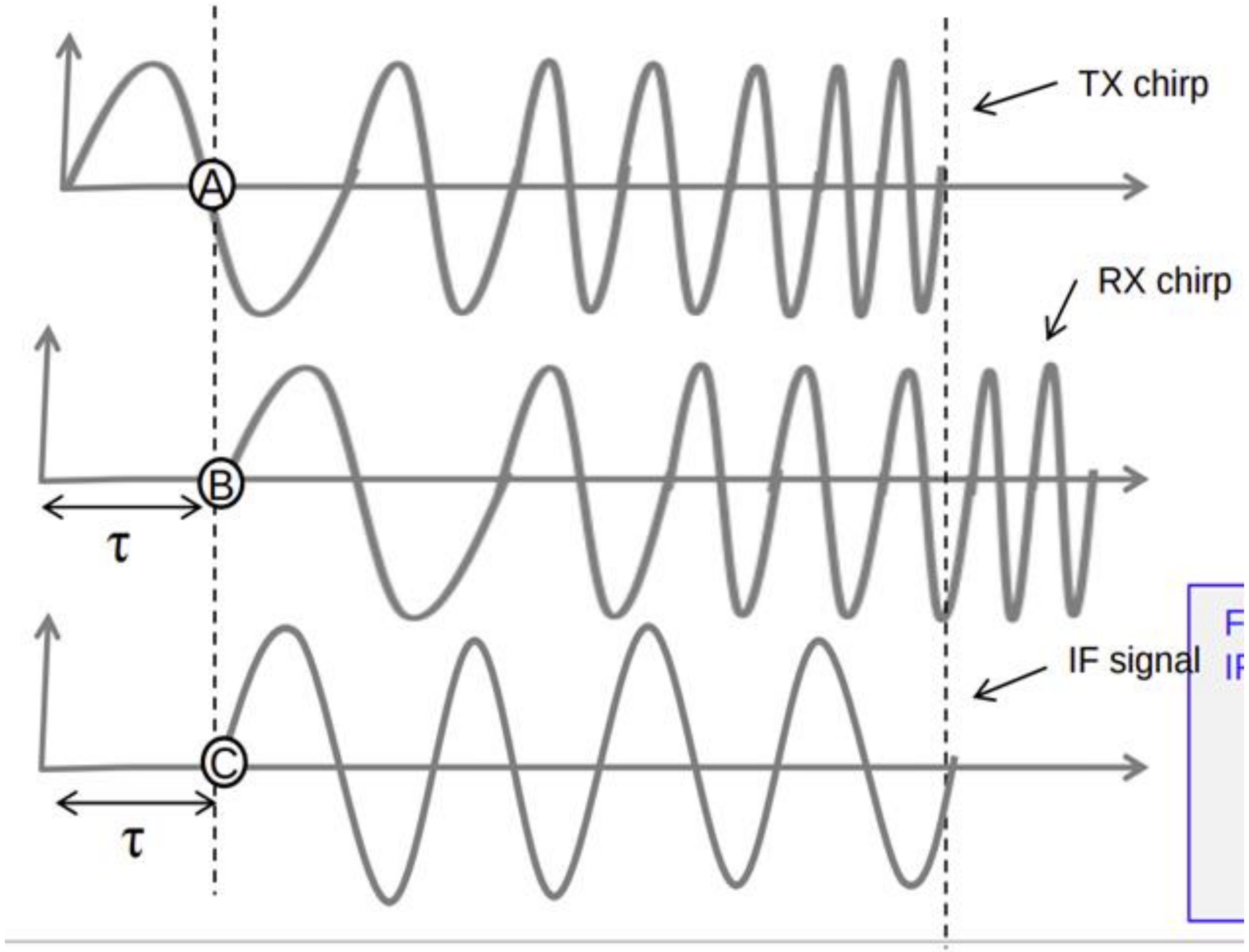

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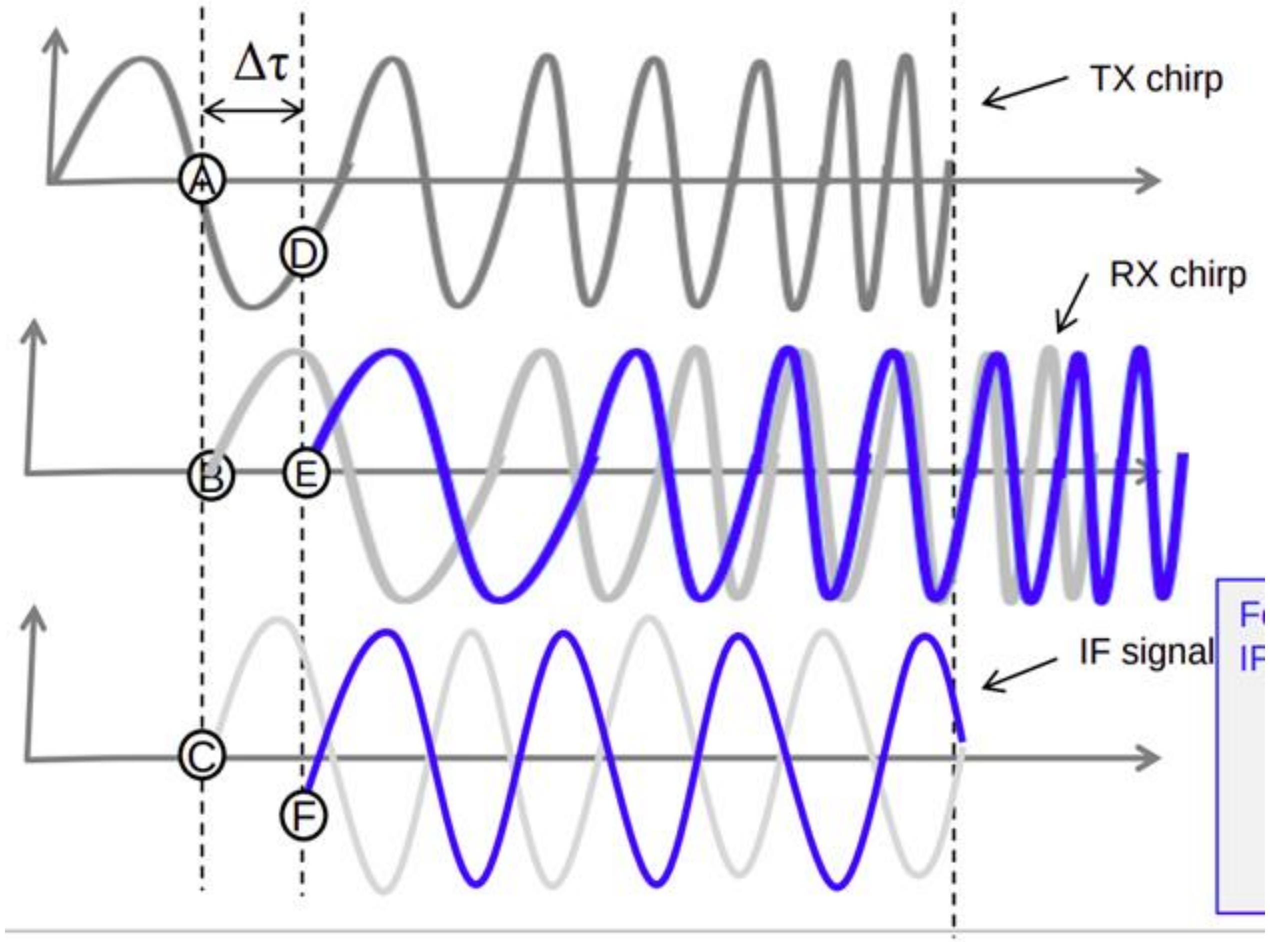
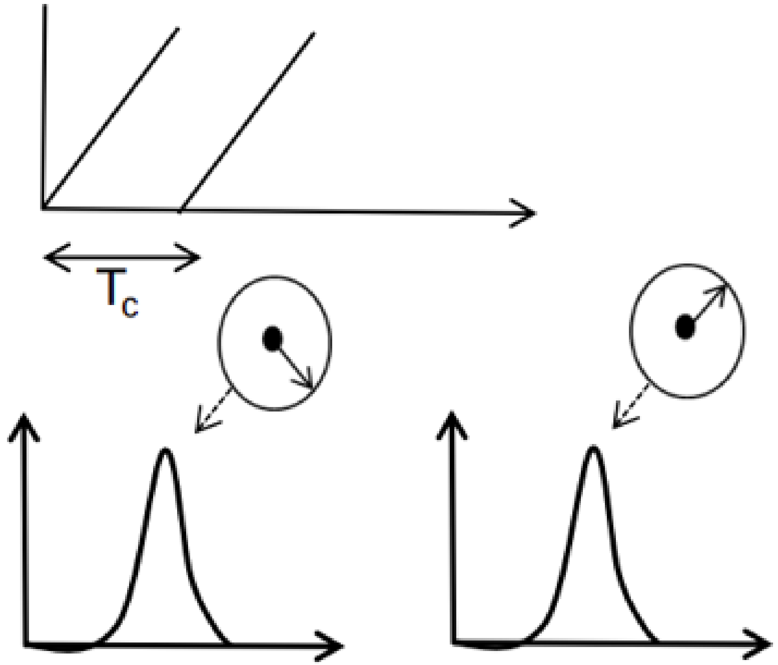


- Phase difference between (A and D) or (C and F) is

$$\Delta\Phi = 2\pi f_c \Delta\tau = \frac{4\pi\Delta d}{\lambda}$$



FMCW Radar: Phase of the IF Signal

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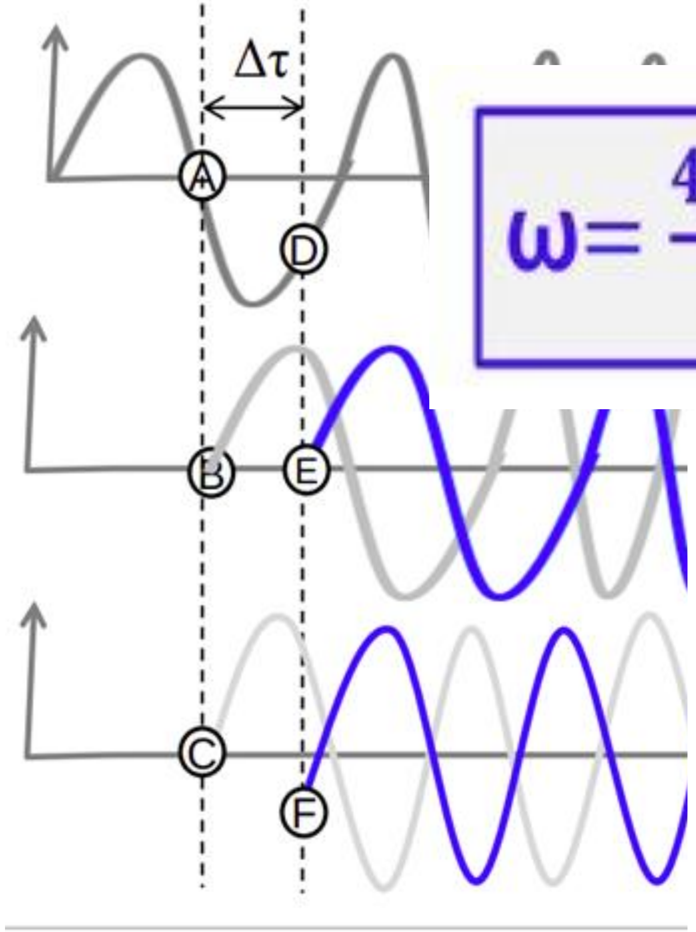
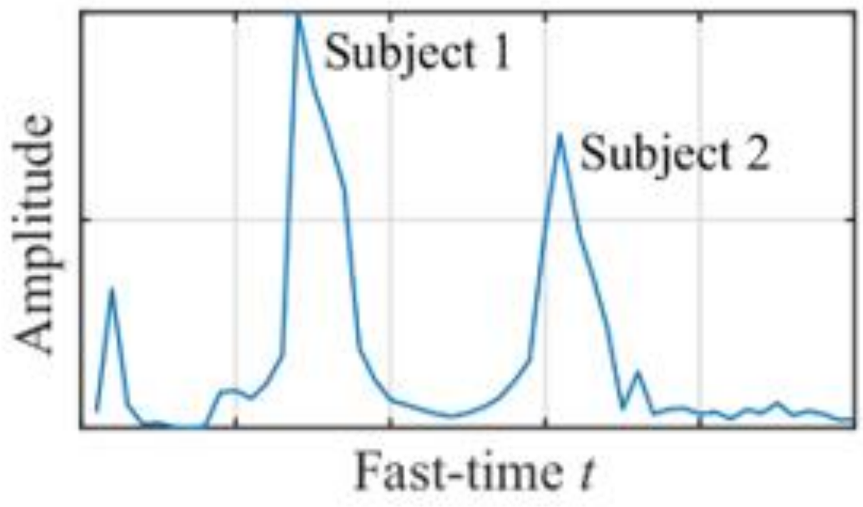
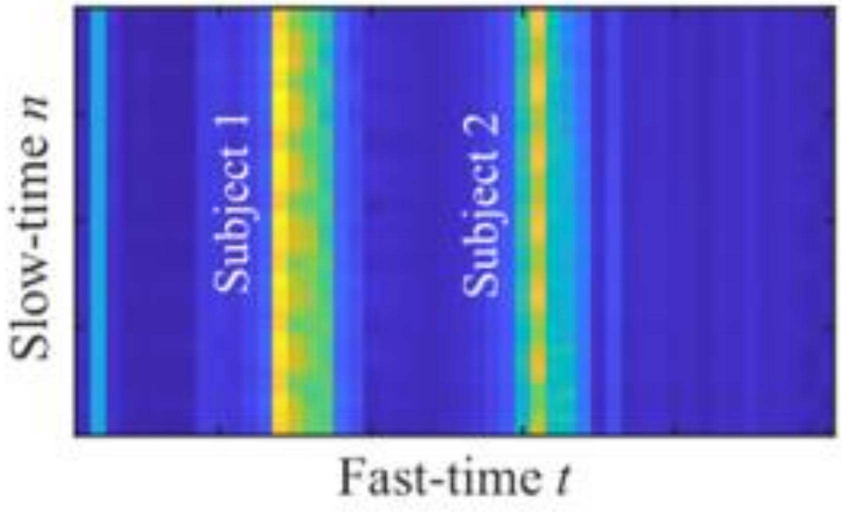


$$\boxed{\omega = \frac{4\pi v T_c}{\lambda} \Rightarrow v = \frac{\lambda\omega}{4\pi T_c}}$$



(a) Signal frame $|r(t)|$.

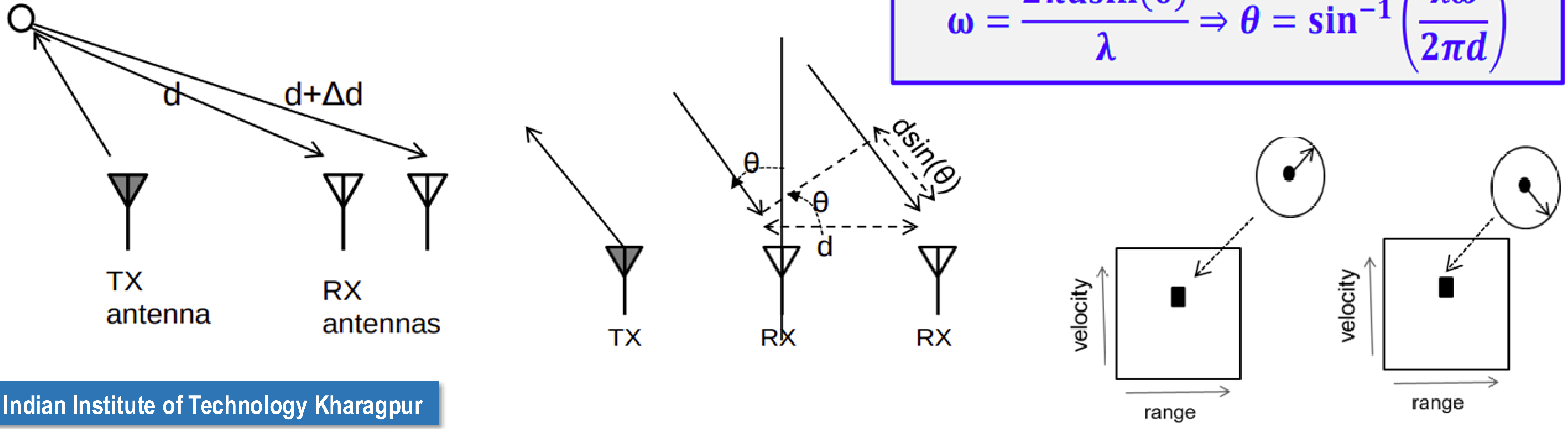


(b) Signal matrix $|\boldsymbol{r}(t)|$.

FMCW Radar: AoA Estimation

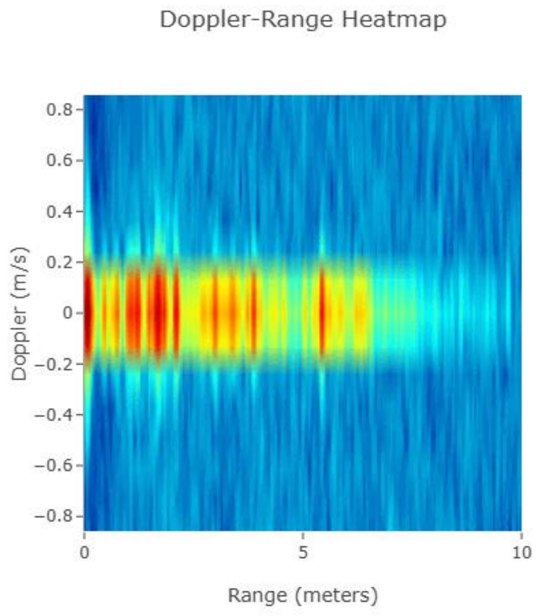
- TX antenna transmits a frame of chirps
- The 2D-FFT corresponding to each RX antenna will have peaks in the same location but with differing phase.
- The measured phase difference (ω) can be used to estimate the angle of arrival of the object.

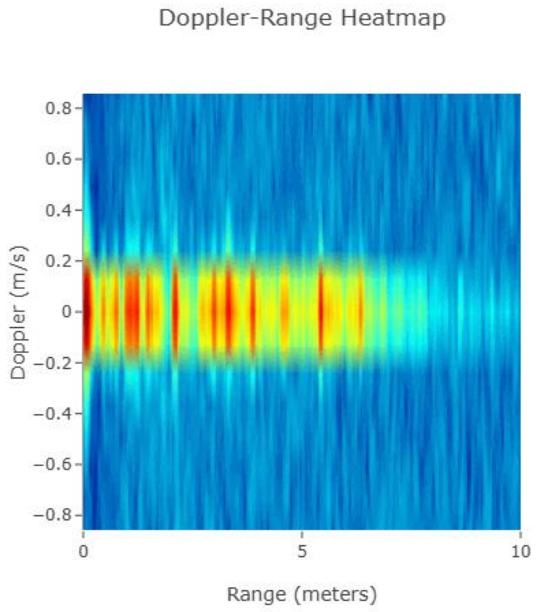
$$\boldsymbol{\omega = \frac{2\pi d \sin(\theta)}{\lambda} \Rightarrow \theta = \sin^{-1}\left(\frac{\lambda\omega}{2\pi d}\right)}$$

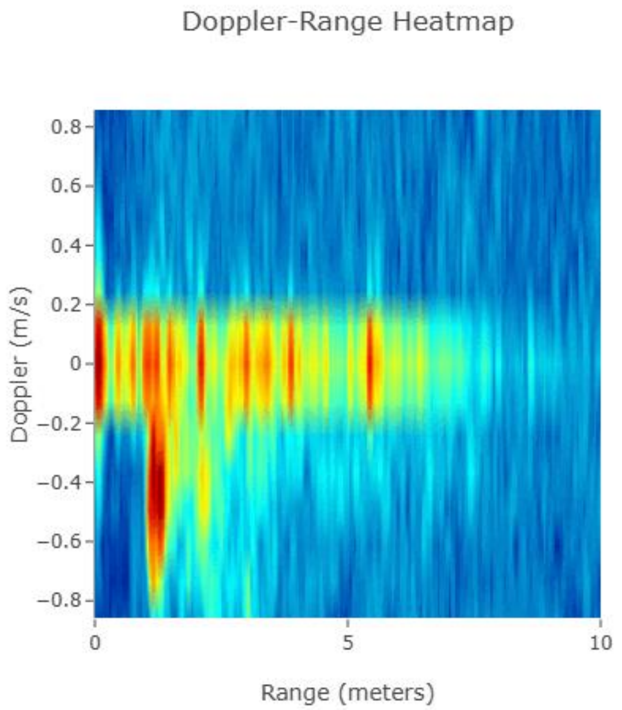


Visualizing and Analyzing mmWave Radar Data

- **Rangle-Doppler heatmap**:
  - Represents the detected objects' distances (range) and relative velocities (Doppler shift); each point corresponds to a unique combination of range and Doppler values
  - intensity of each point indicates the strength of the reflected signal (probability that an object is being present in that range)







Visualizing and Analyzing mmWave Radar Data

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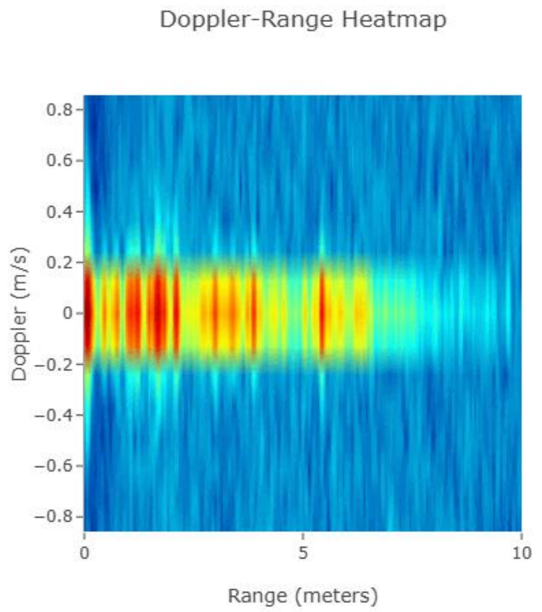
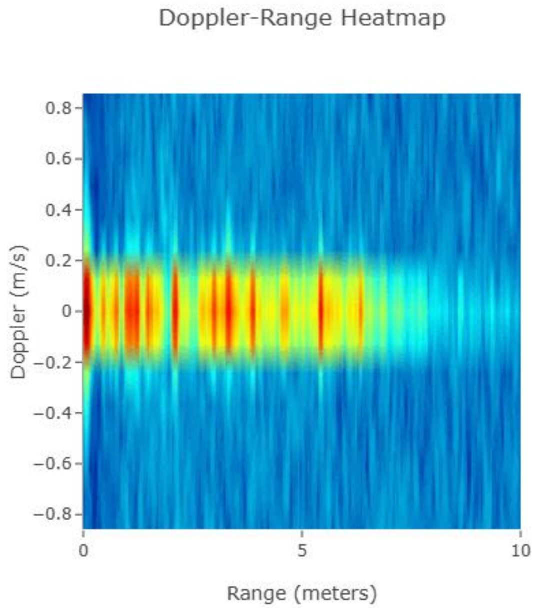
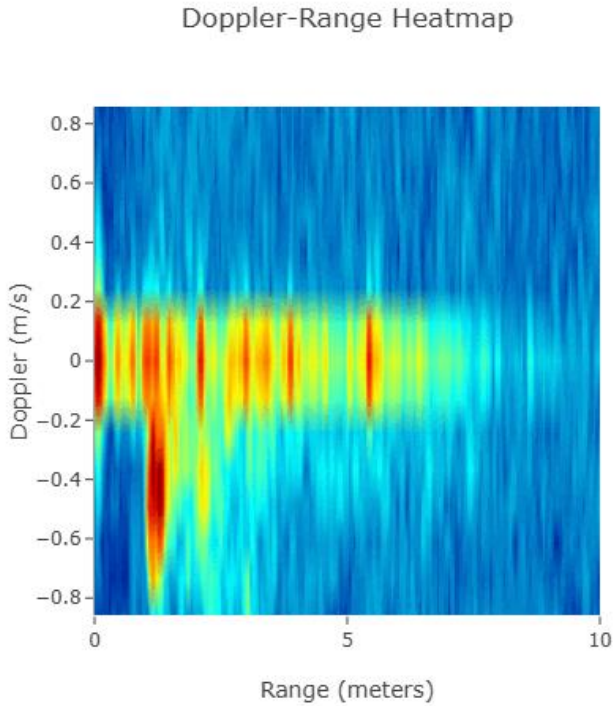
    - Represents the detected obj shift); each point correspond
    - intensity of each point indica an object is being present in

Why do we see a high intensity at zero-doppler?

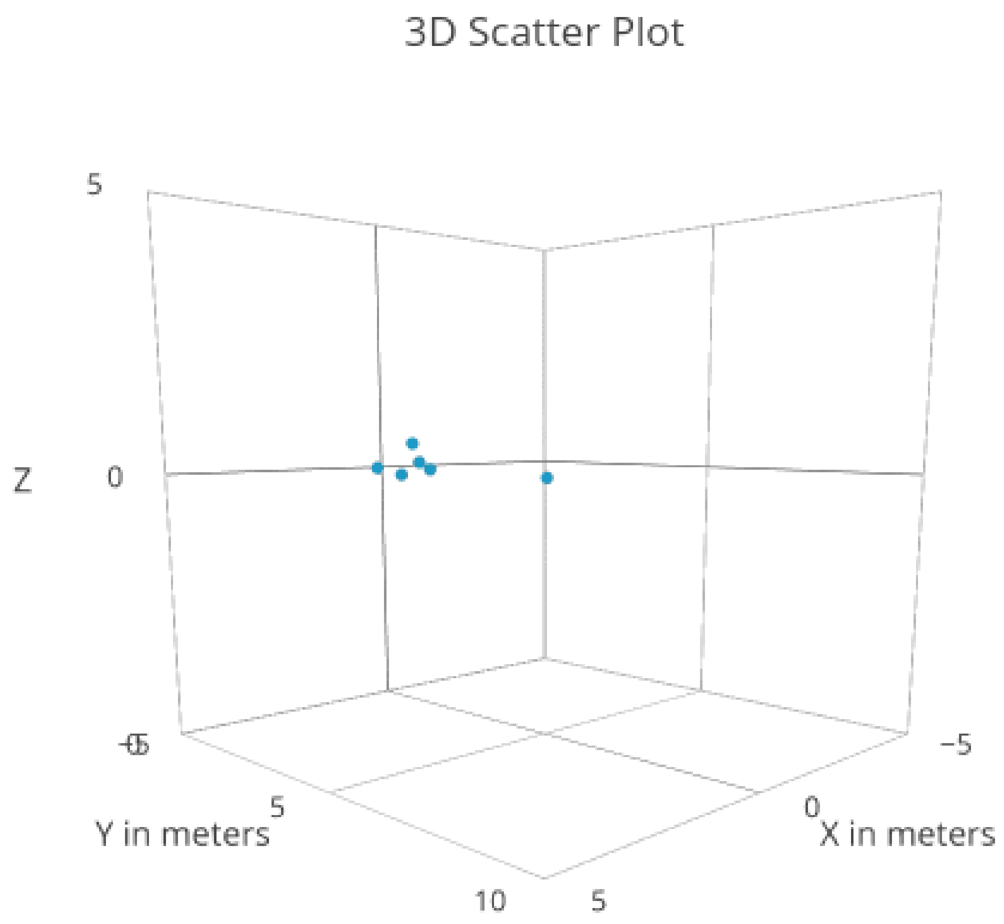






Visualizing and Analyzing mmWave Radar Data

- **Point Cloud Data (PCD)**:
  - A collection of data points in 3D space that represents the positions of objects detected by the radar (**A point where a radar reflection is detected**)
  - Generated from distance (range), relative velocity (Doppler) and AoA -- Each detected point is mapped to a specific 3D coordinate based on range, angle, and Doppler information.



Analyzing mmWave Data

- **1D FFT (Range FFT) to extract the Range Information**
  - Use the beat frequency (FFT over the IF signal) to compute the range bins
  - Each peak in the range FFT corresponds to an object at a specific distance

- **2D FFT across Chirps (Doppler FFT)**
  - A second FFT is performed across the slow time axis, which corresponds to the sequence of chirps
  - Reveals the Doppler frequency shift caused by the relative motion of objects with respect to the radar

- **Angle FFT**
  - A third FFT at the spatial dimension (across antennas) to capture the AoA

Continuous Multi-user Activity Tracking via Room-Scale mmWave Sensing

ARGHA SEN, ANIRBAN DAS, SWADHIN PRADHAN, SANDIP CHAKRABORTY

IIT KHARAGPUR

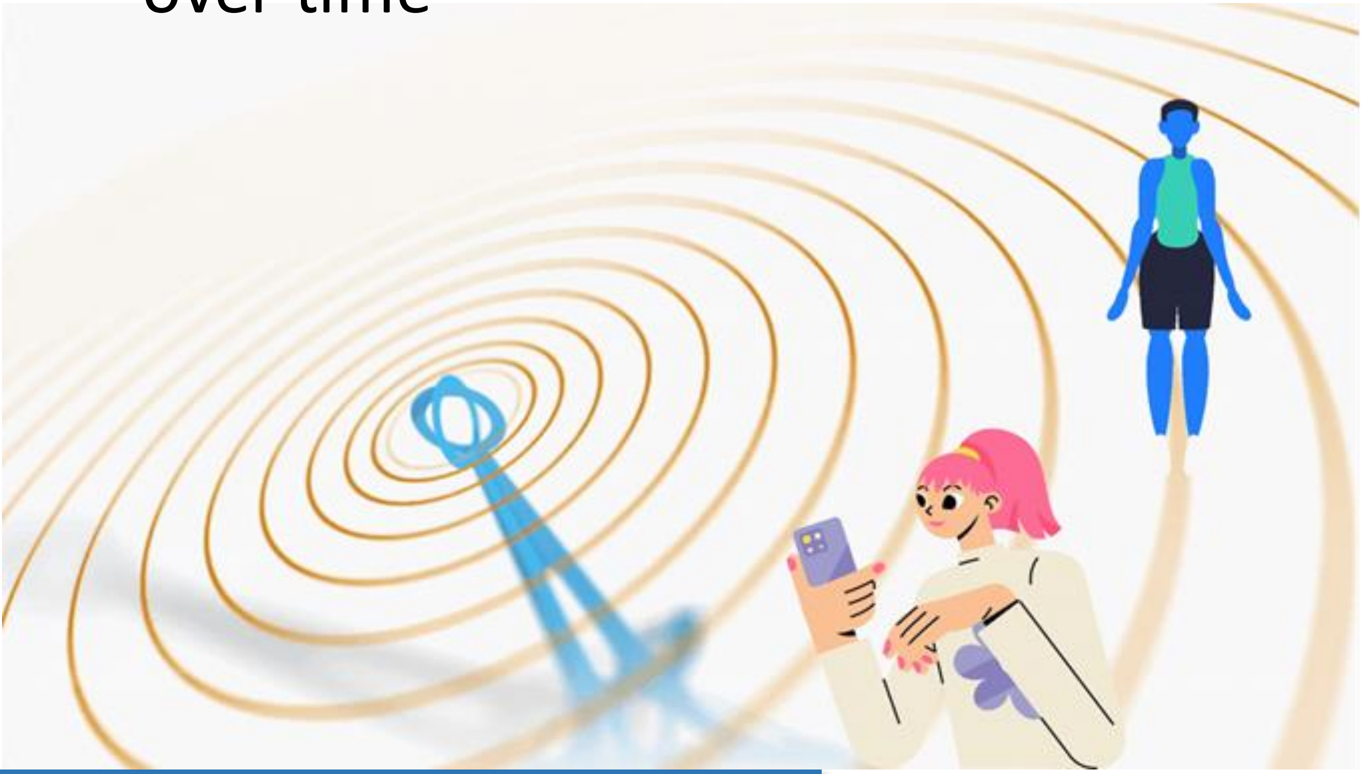
ACM/IEEE IPSN 2024

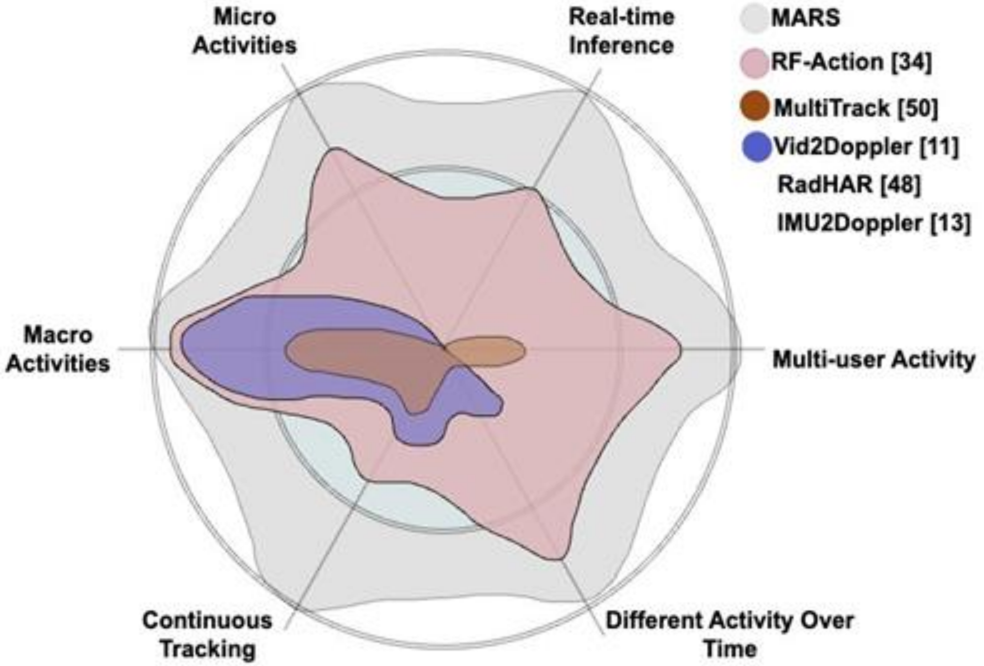
Your Home Knows You Well

Generated through GPT-4

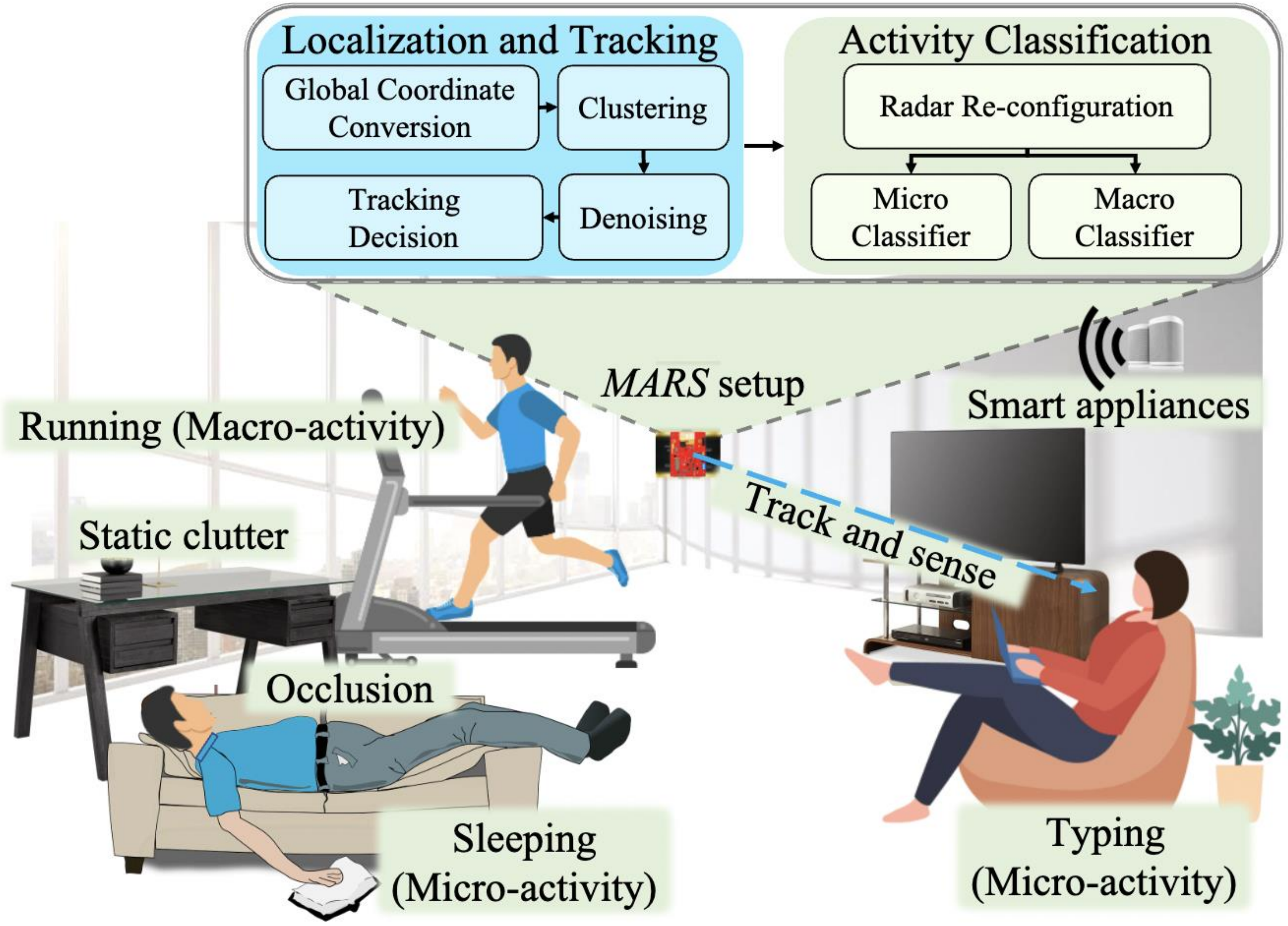
Requirements

- Continuous subject tracking
- Monitoring multiple subjects
- Monitoring different activities over time
- Real-time inference of activities
- Multi-activity support
    - Both in micro-scale as well as macro-scale

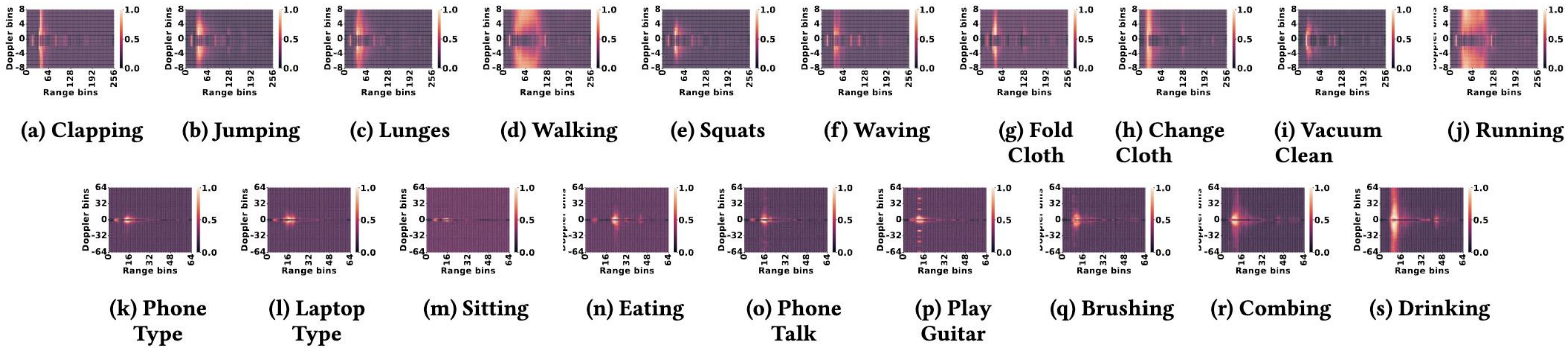




The Broad Vision Towards a Feasible Solution



Which Activities Can be Sensed?



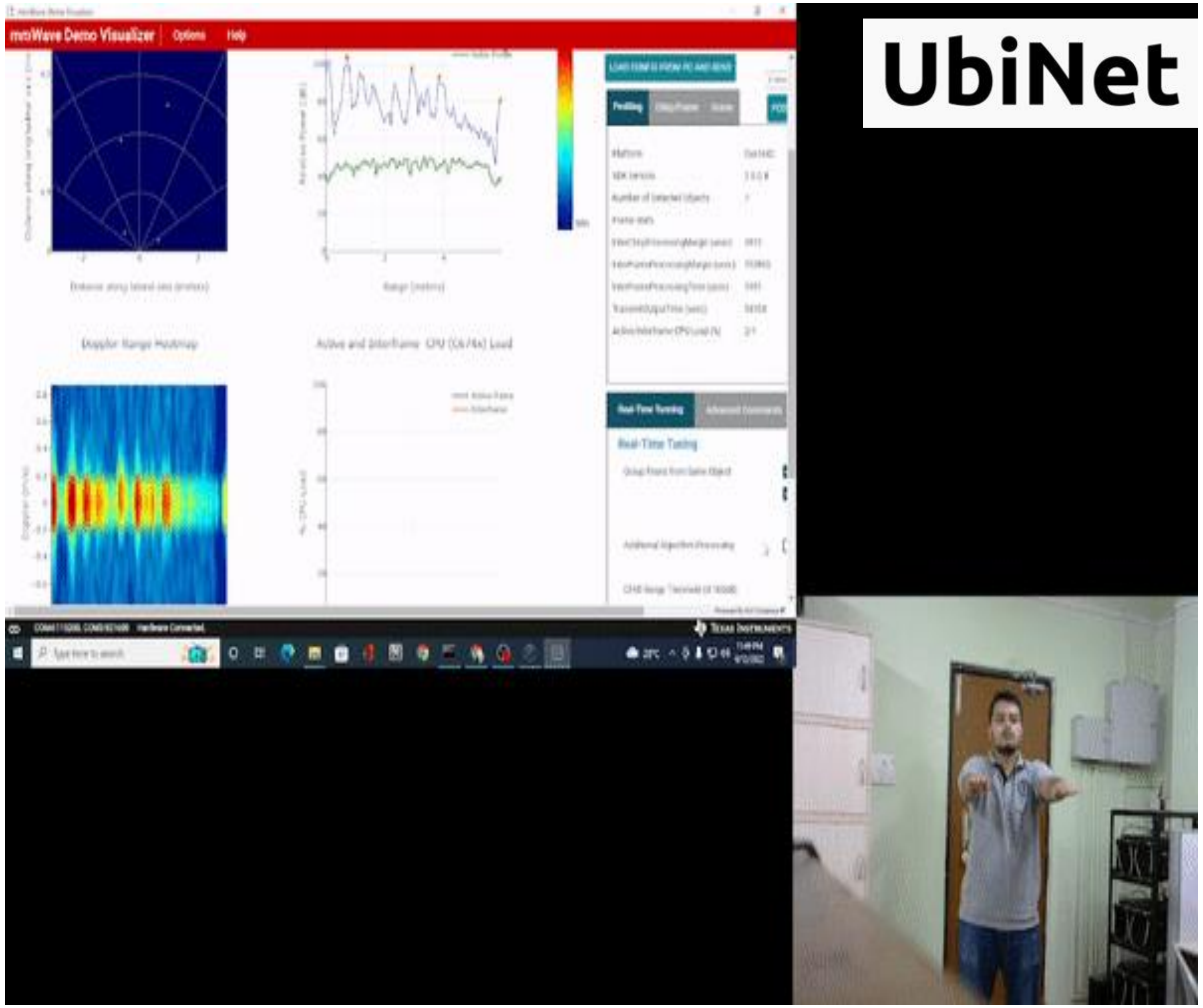
(a) Clapping (b) Jumping (c) Lunges (d) Walking (e) Squats (f) Waving (g) Fold Cloth (h) Change Cloth (i) Vacuum Clean (j) Running

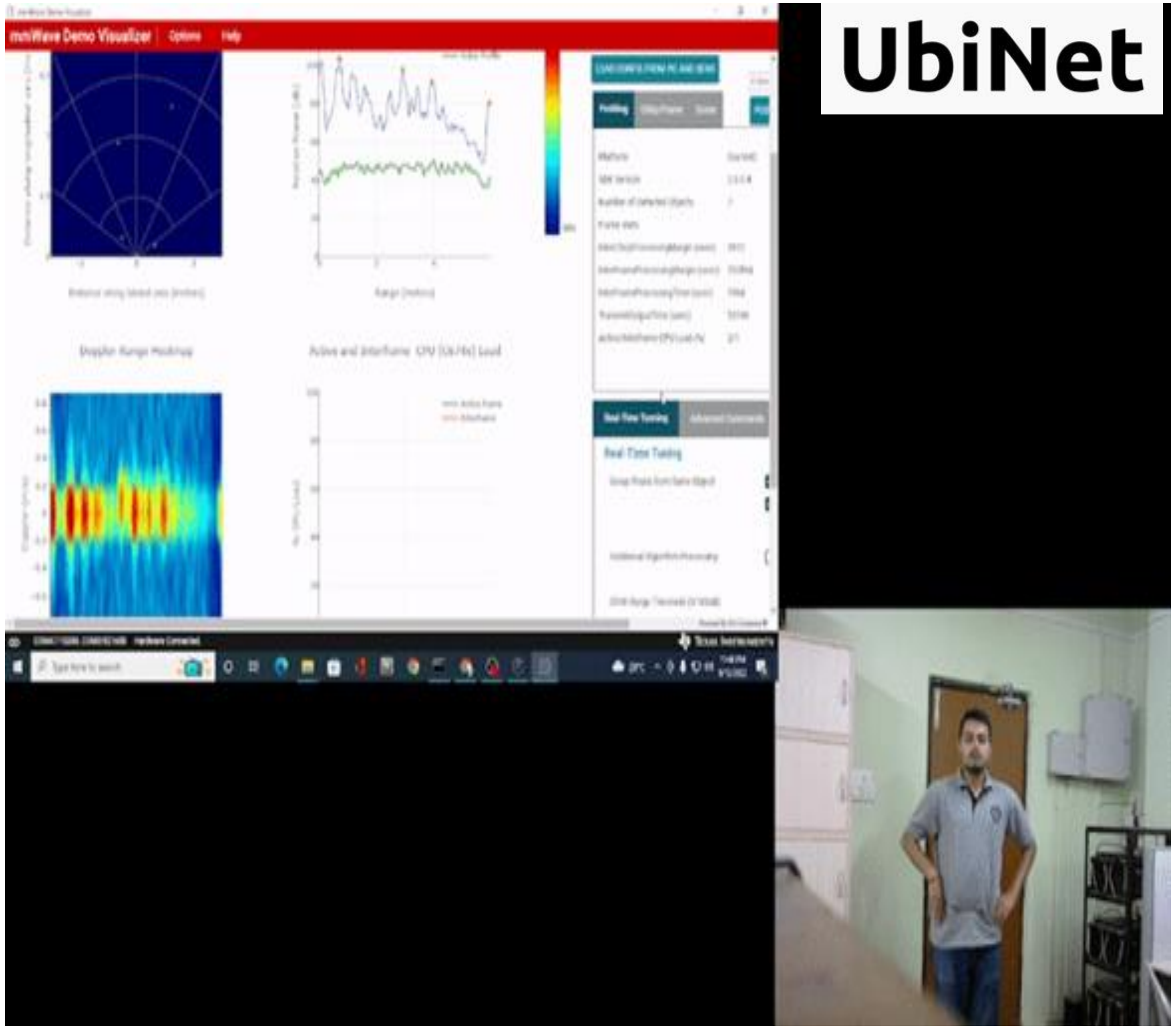
(k) Phone Type (l) Laptop Type (m) Sitting (n) Eating (o) Phone Talk (p) Play Guitar (q) Brushing (r) Combing (s) Drinking

- We primarily consider
  - Activities of Daily Living (ADLs)
  - Instrumental Activities of Daily Living (IADLs)
  - Exercises

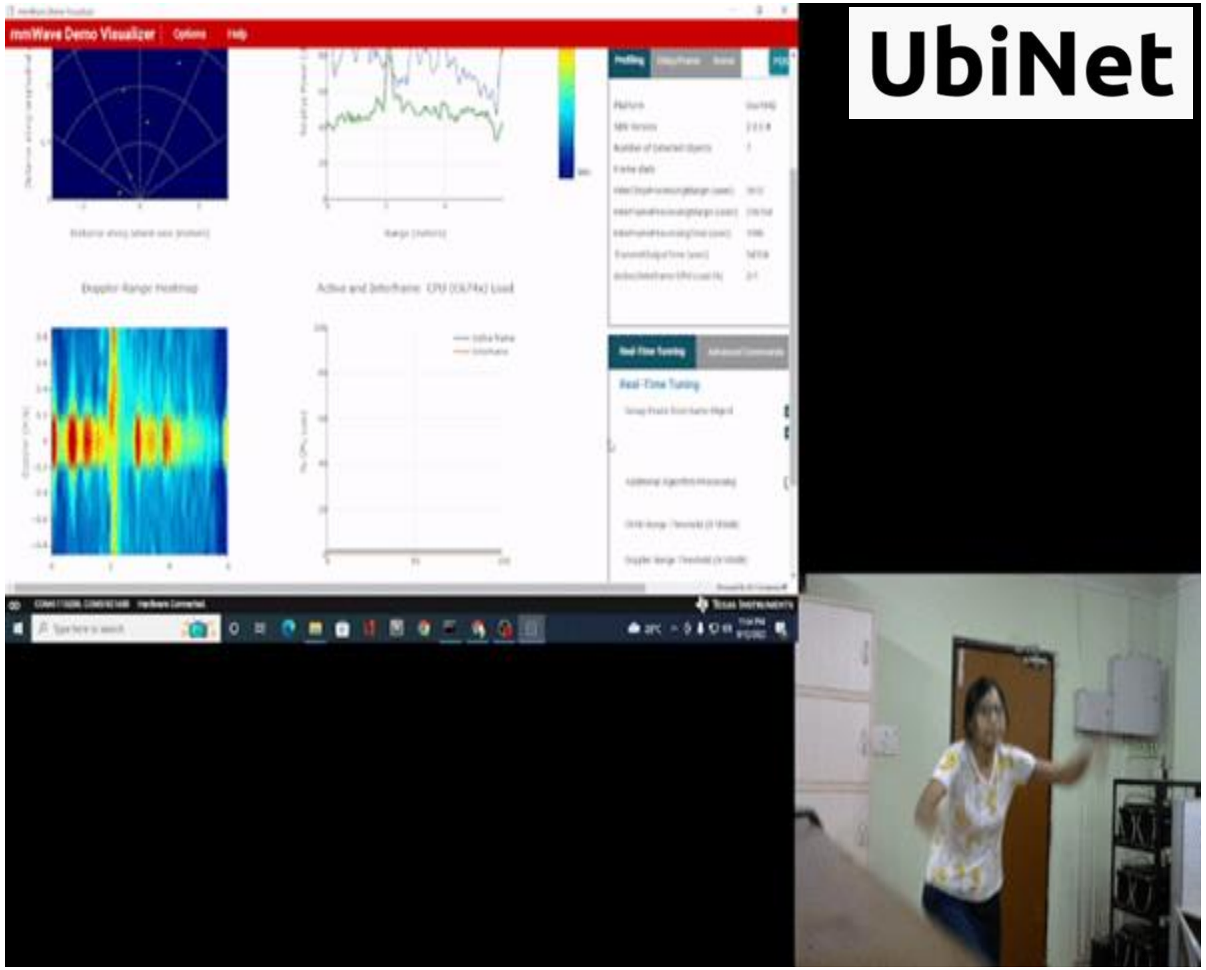
- Need **different doppler resolutions** for macro (-8 to 8) and micro (-64 to 64) activities to separate
- The **temporal changes** are also important
  - Running has much faster temporal changes than walking

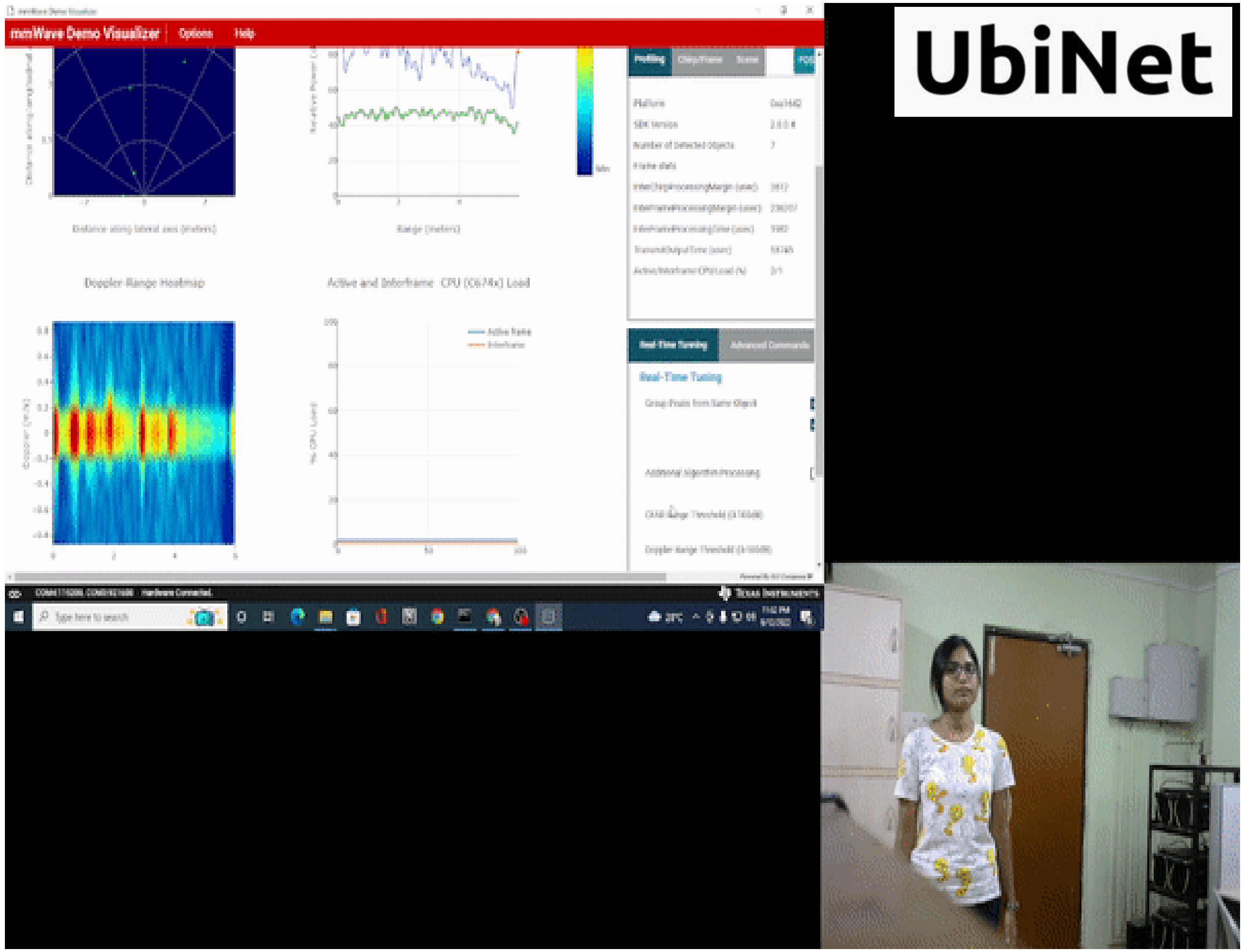
Examples: Exercise



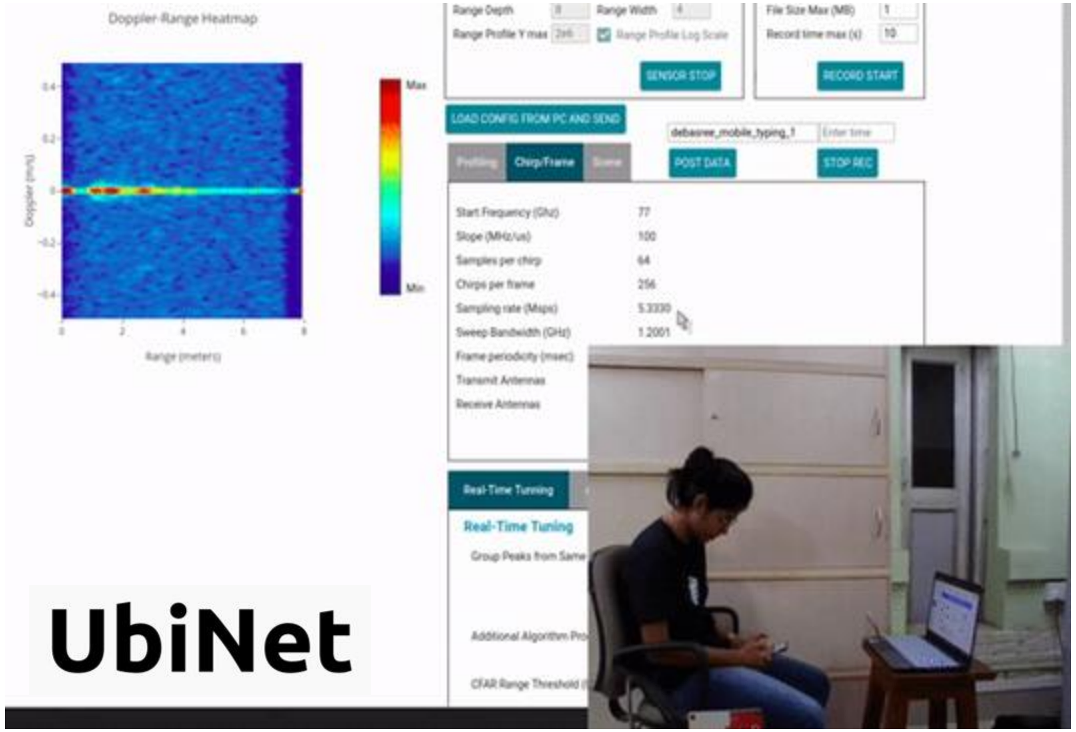


Examples: Different Jumping Activities

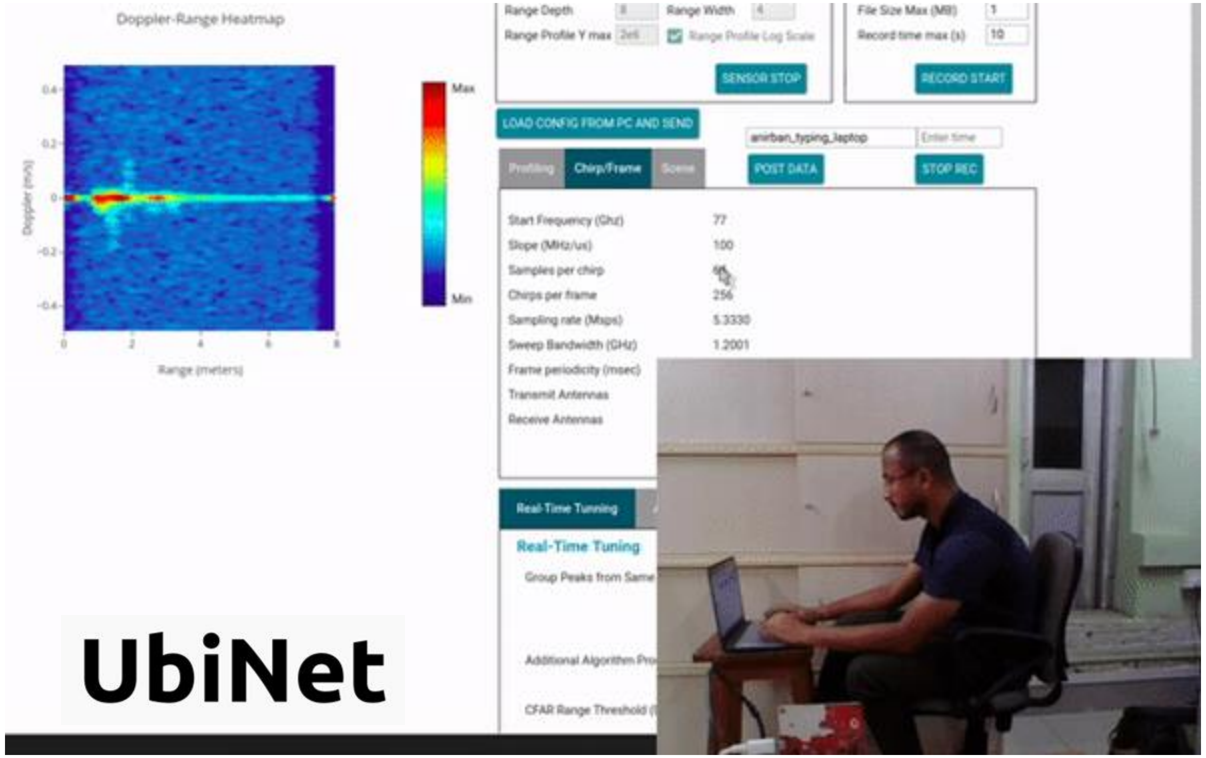




Examples: Micro Activities



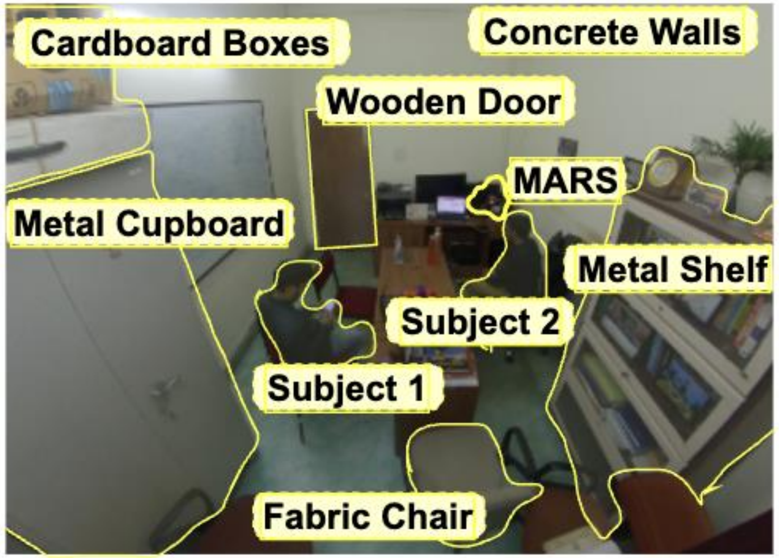
Using Phone

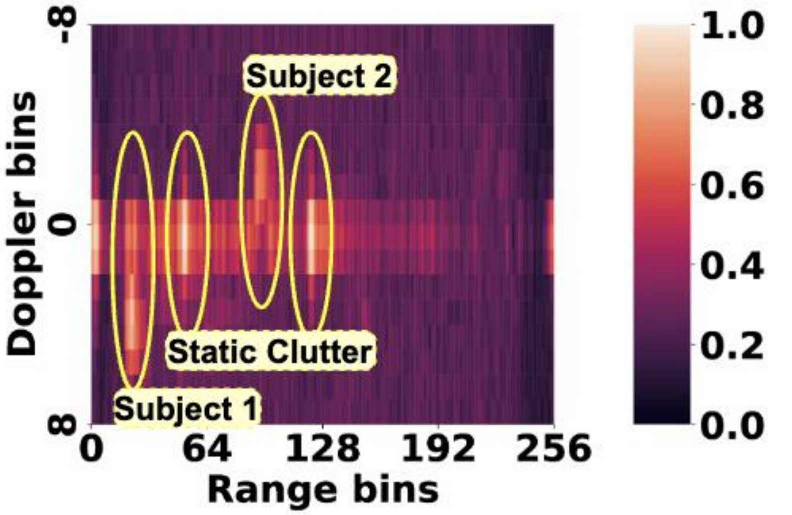


Using Laptop

Impact of Static Clutters

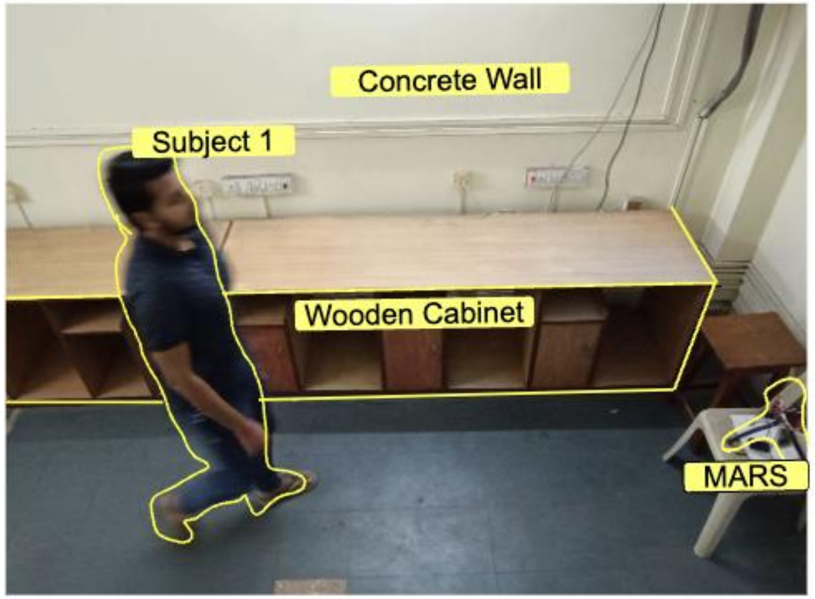
- Any object which are stationary but can reflect the mmWave signals
  - Walls, furniture, etc.
- We observe multiple peaks at the range bins
- Static clutters produce a higher magnitude along the zero doppler axis
  - Signifying near-zero or no movements

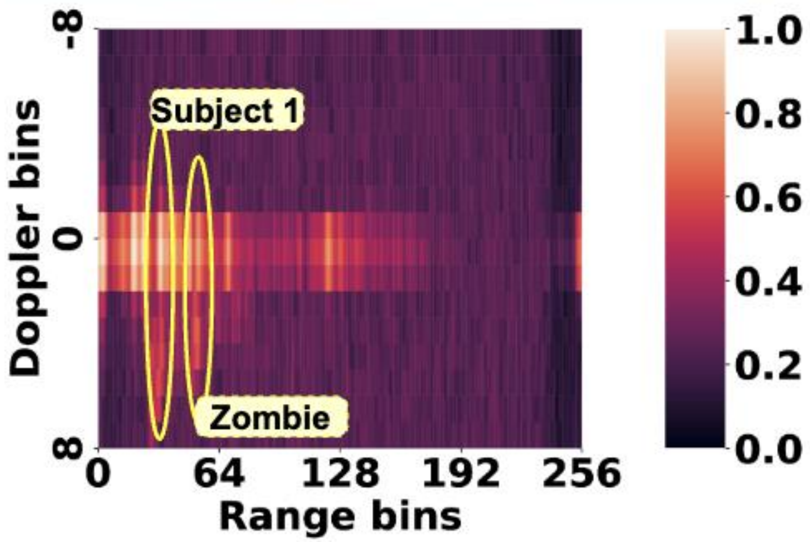




Impact of Non Line of Sight (NLoS)

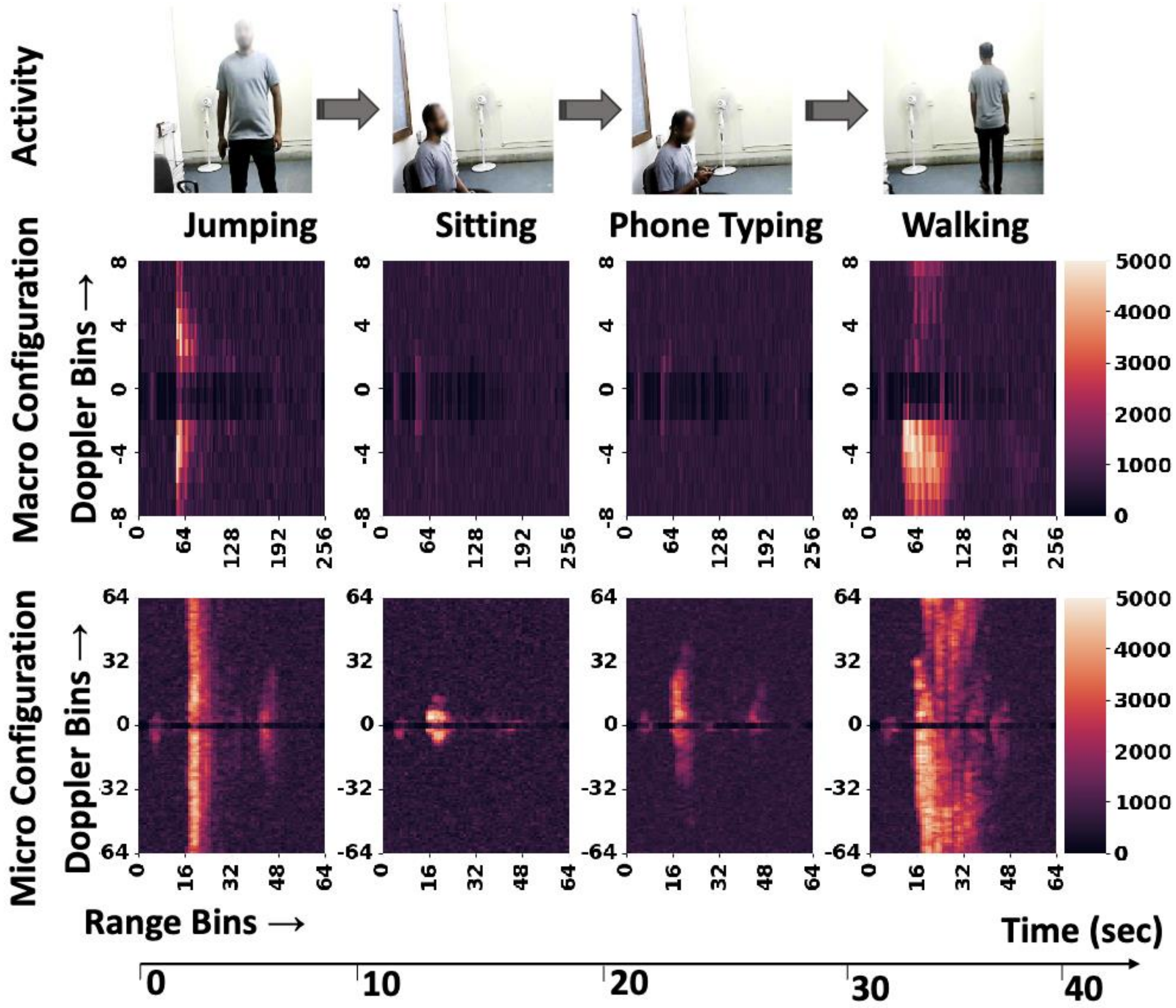
- The subject stands near the wall and then makes some movements
  - The NLoS reflections from the wall creates a signature on the range-doppler heatmap (we call them as **zombie**)
- Zombie has a lower peak than the original subject
  - Need a method to extract the signatures from the zombies





Radar Configuration

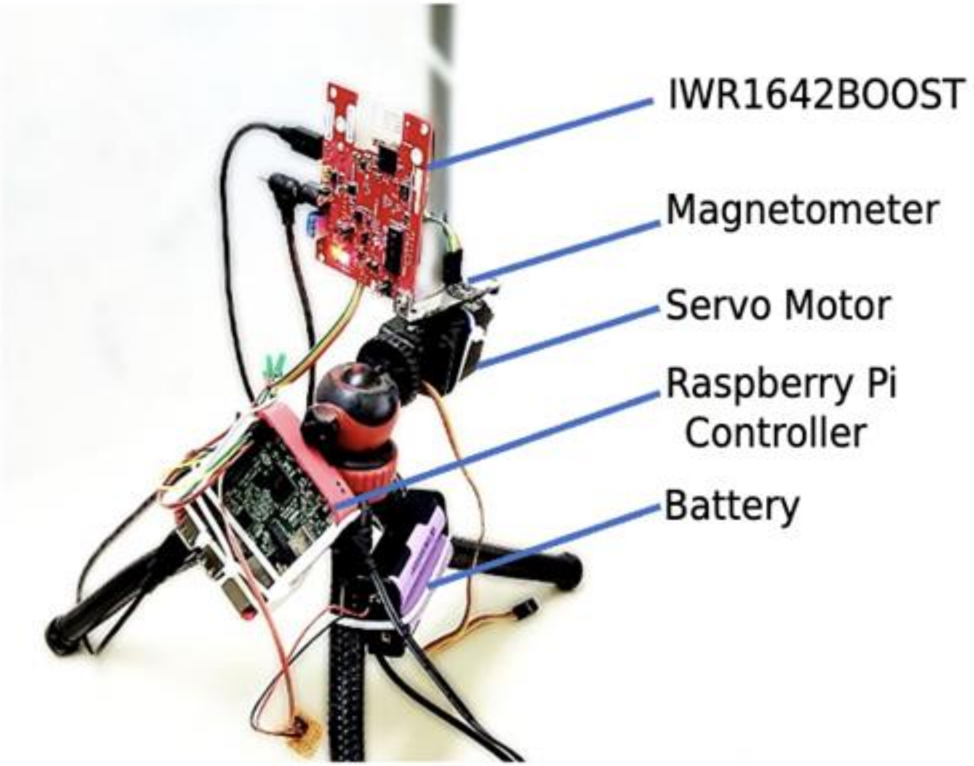
- Different types of activities are detectable at different doppler resolutions!



MARS (Multi-user Activity Tracking via Room-scale Sensing)

- Mount the radar on top of a servo
  - A magnetometer to track the movement of the servo

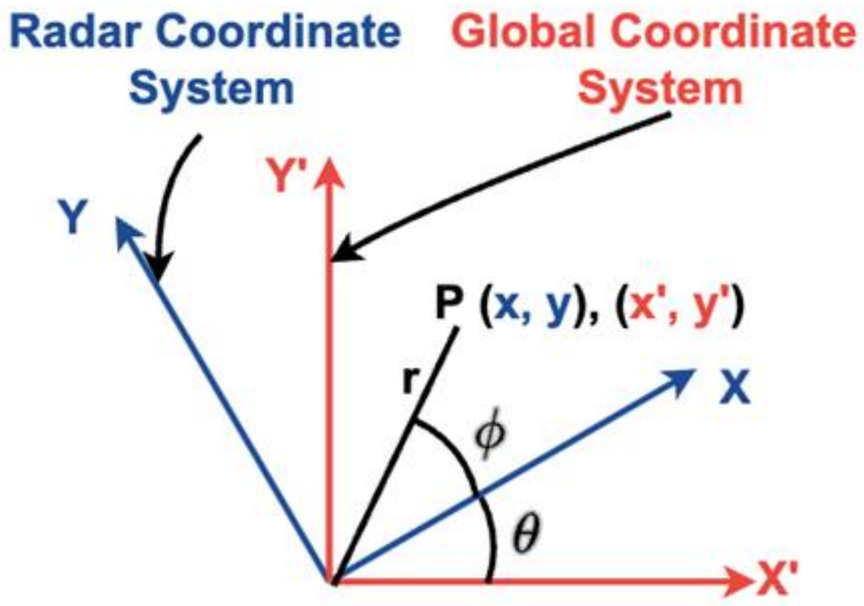
- Lifecycle of the radar
  - Detect a user from point-cloud data
  - Localize and track the user
  - Check the macro activity
  - Switch the radar configuration
  - Check the micro activity
  - Switch the radar configuration

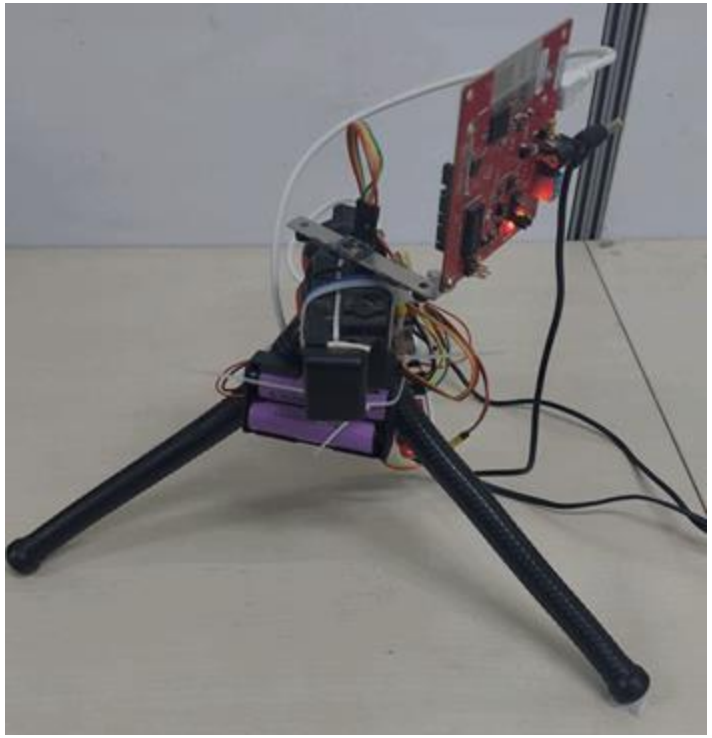


Point and Track with Configuration Switching

MARS System Architecture

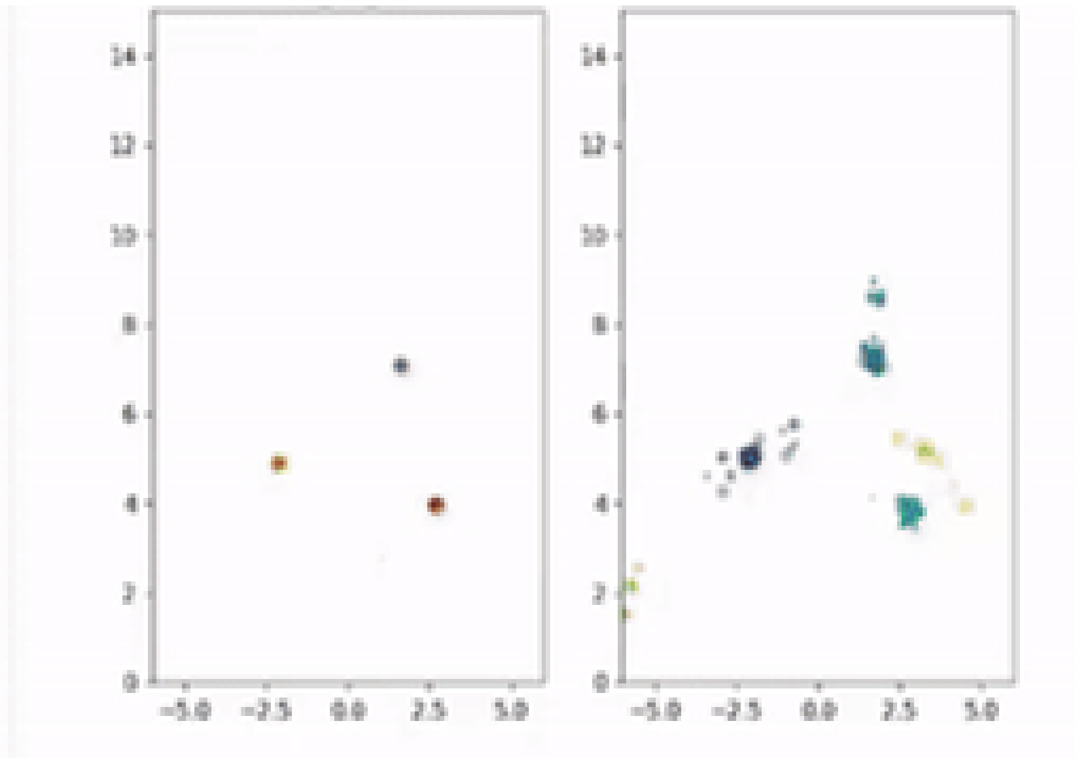
- **Localization and Tracking Pipeline**
  - Isolate subjects from static clutters (using zero doppler)
  - **Rotating the radar changes the coordinates of the point clouds**: Set up a global reference coordinate with respect to the magnetometer





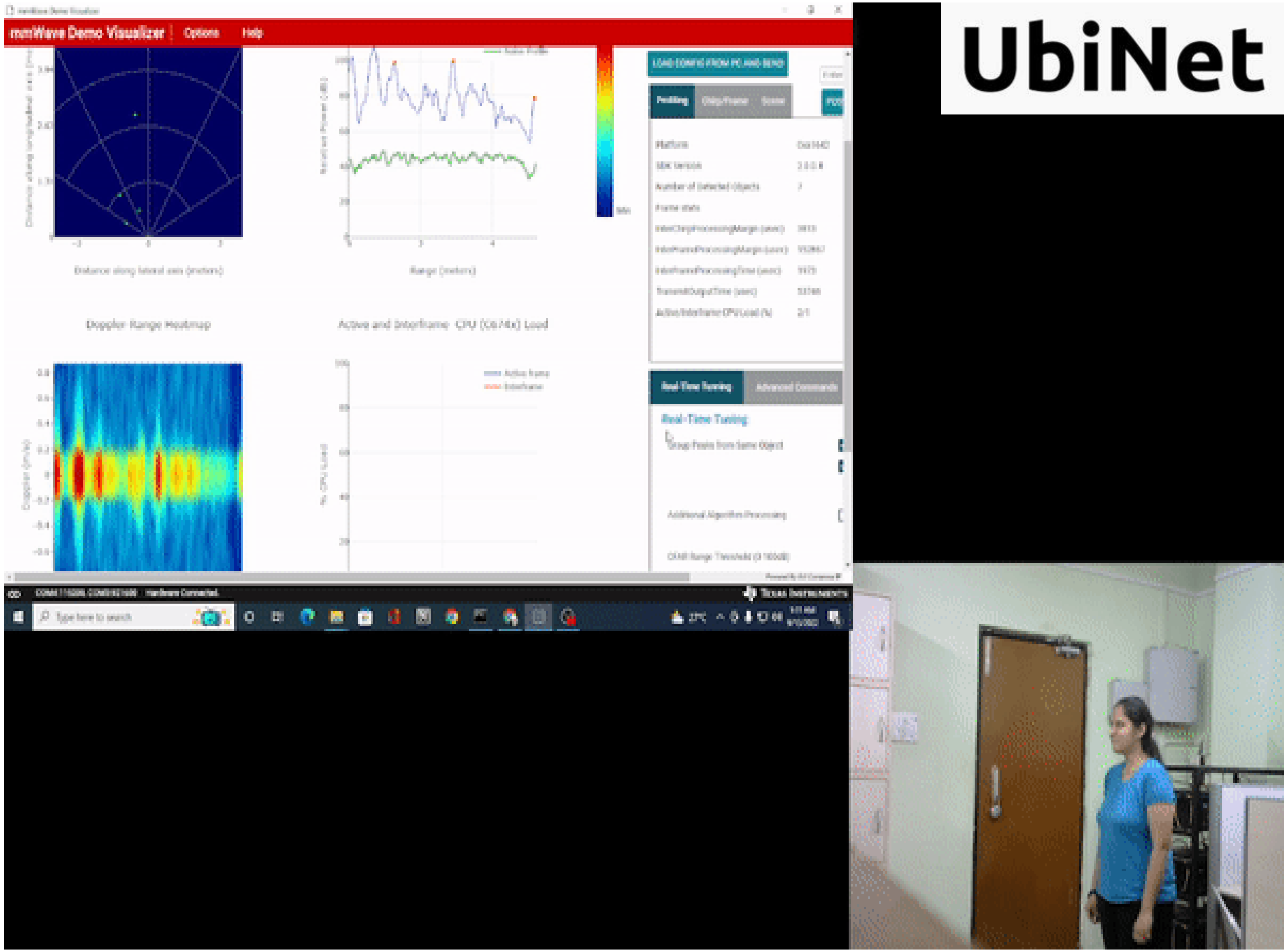
MARS System Architecture

- **Tracking Multiple Subjects:** Use DBSCAN to cluster the pointcloud data
  - Compare two clusters to check whether a new subject has been introduced in the system

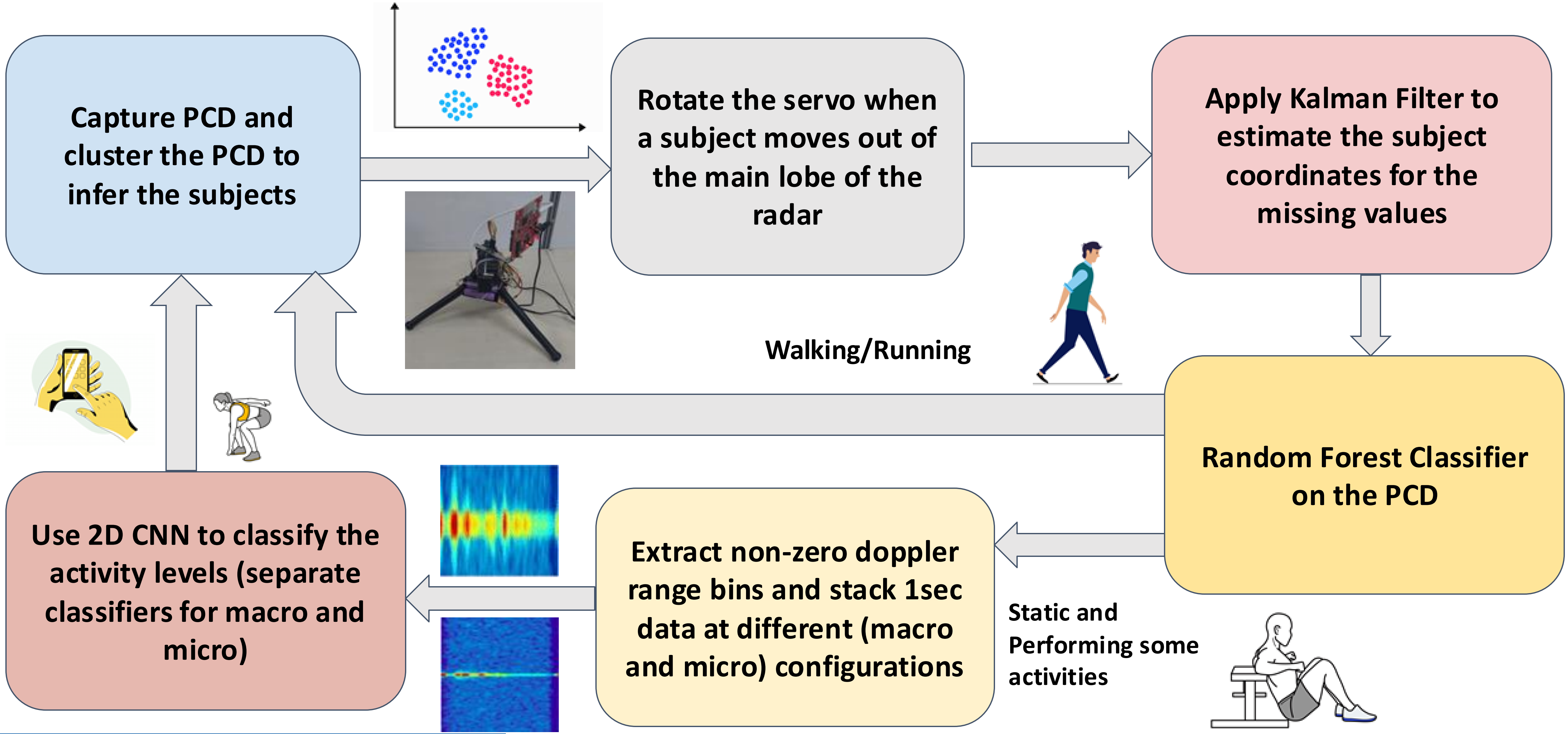


Handling Blind Spots

- Two user crosses each other, creating blind spots
- We use a **Recursive Kalman Filter (RKF)** to track the subjects movement states continuously
  - Estimate when the actual Point Cloud Data (PCD) is unavailable due to occlusion



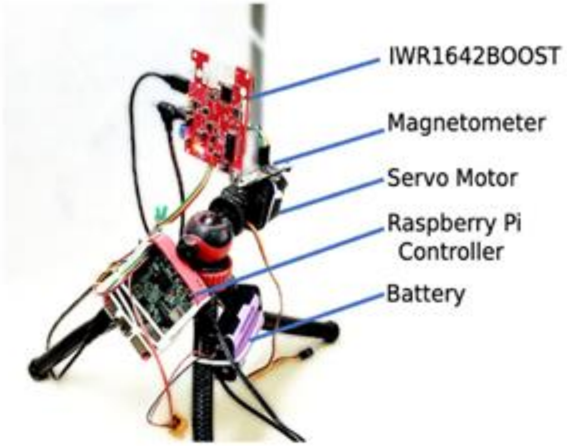
The High Level Processing Pipeline



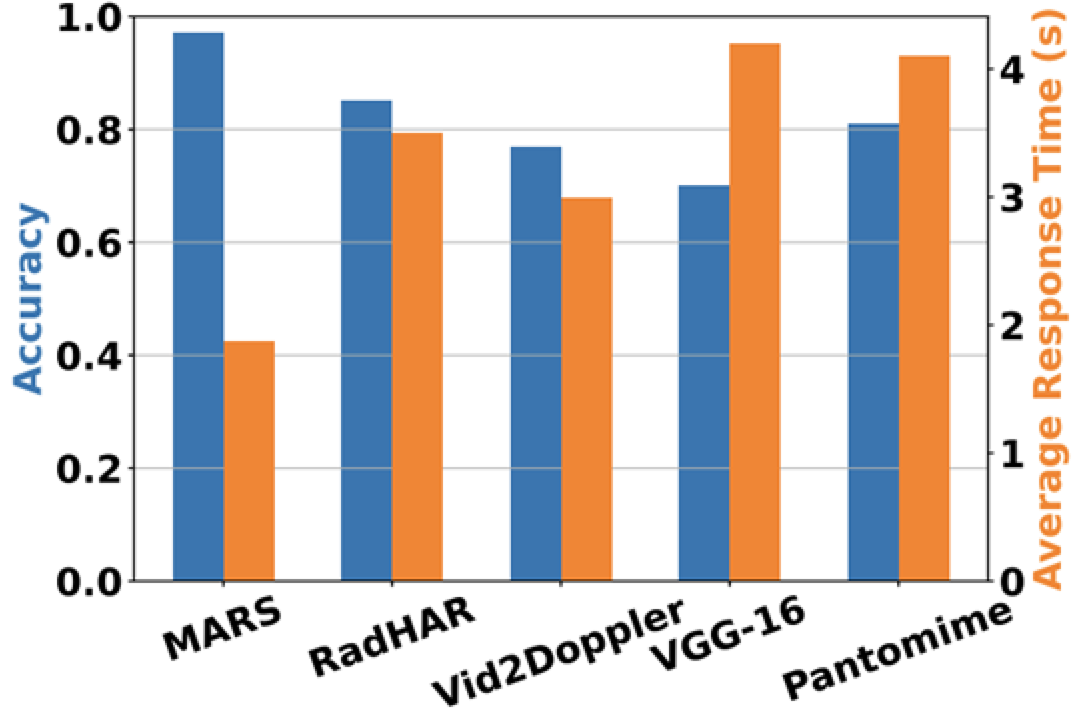
Implementation and Testing

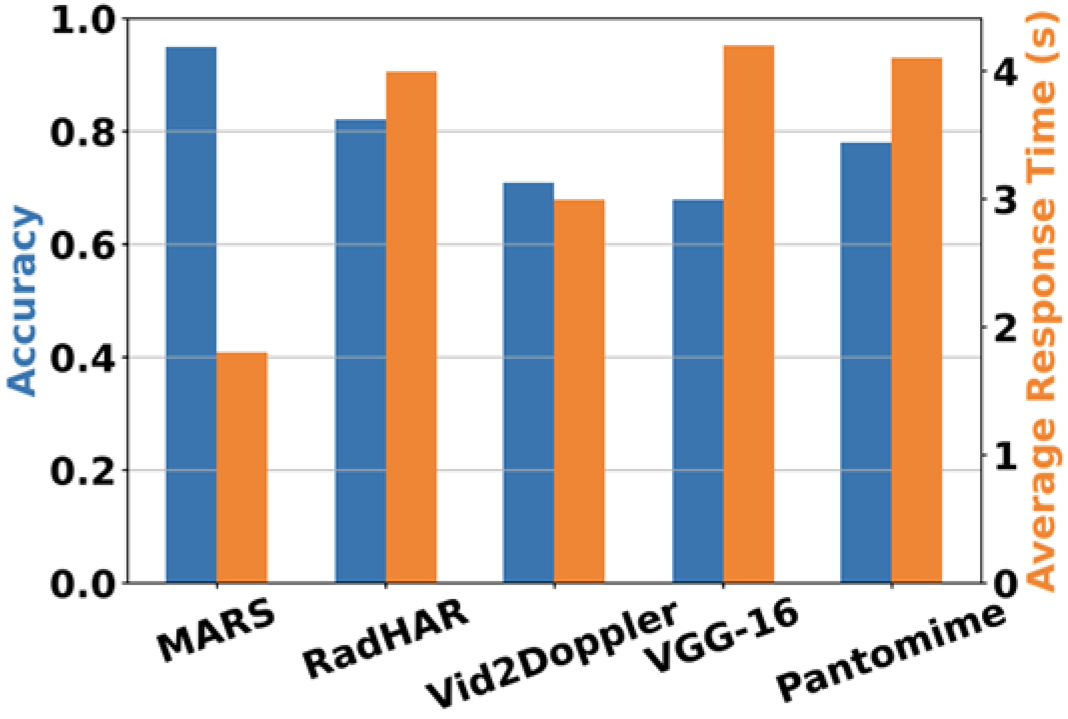
- The processing pipeline has been implemented on a Raspberry Pi
- We experimented over three different rooms of different sizes
- 7 subjects (3 female, 4 male)

Parameters	Localization	Macro	Micro
Start Frequency	77 GHz		
End Frequency	81 GHz		
Range Resolution (cm)	4.36		12.5
Maximum Range(m)	9.02		6.4
Maximum Radial Velocity (m/s)	1		0.64
Velocity Resolution (m/s)	0.13		0.01
Azimuthal Resolution (Degree)	14.5°		
Frames per Second	30	5	2
Chirps Per Frame	32		64
ADC Samples per Chirp	256		



Accuracy vs Response Times





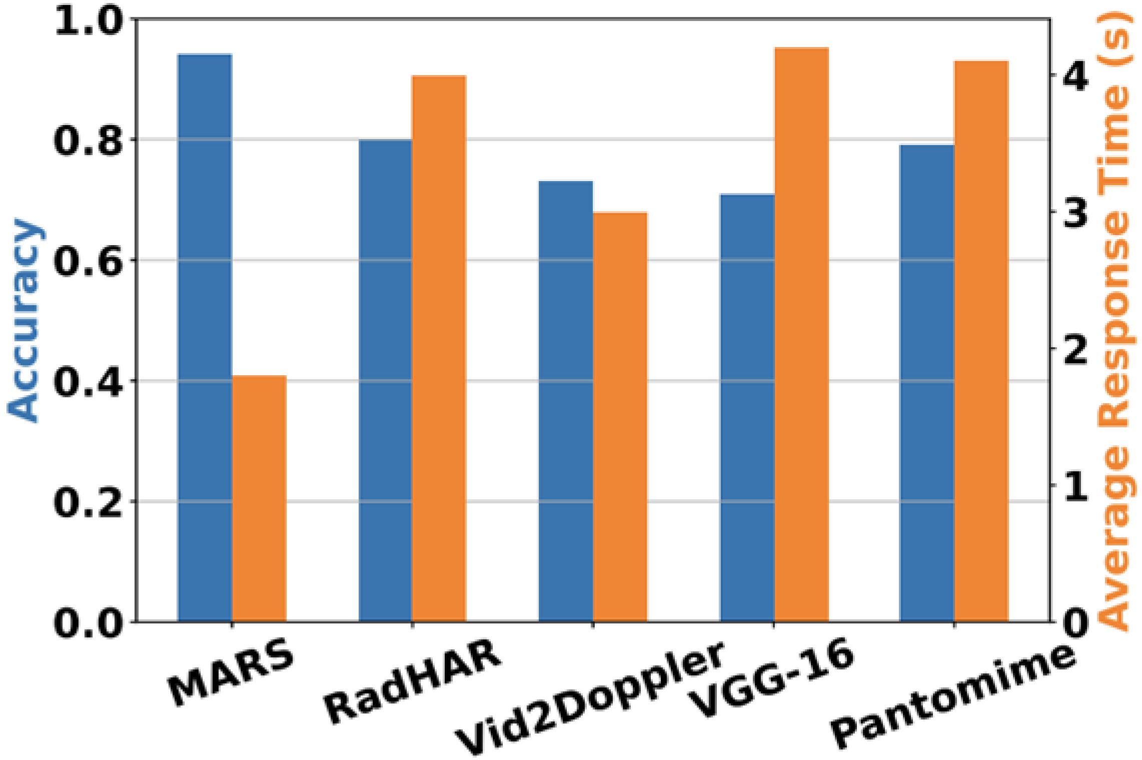
Single User

Perform different activities over time

Multi User (N=3)

Each user performs different activities, no activity switching over time

Accuracy vs Response Times



Multi User (N=3), activity switching over time

PmTrack

Enabling Personalized mmWave-based Human Tracking

HANKAI LIU, XIULONG LIU, XIN XIE, XINYU TONG, KEQIU LI

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ACM IMWUT 2024

Motivation

- **Advantages of mmWave-based Sensing:**
  - High Frequency and large bandwidth
  - High distance, angle and displacement resolution
  - Device free localization with unprecedented accuracy
- **Key Disadvantage:**
  - But, tagging human beings uniquely based on radar data is challenging
- **Why Tagging is Important?**
  - To enable highly intelligent and **personalized** applications

PmTrack: Key Idea

- Identifying “Who carries which IMU?”
  - Determine which IMU data corresponds to which radar data
- Using two modalities
  - mmWave Radar
  - IMU data
- To make the association
  - mmWave
    - Collecting the trajectory data
    - The orientation given by the direction
  - IMU Data
    - Yaw as the orientation
  - **Key Idea –**
    - Finding similarity between these two orientation values

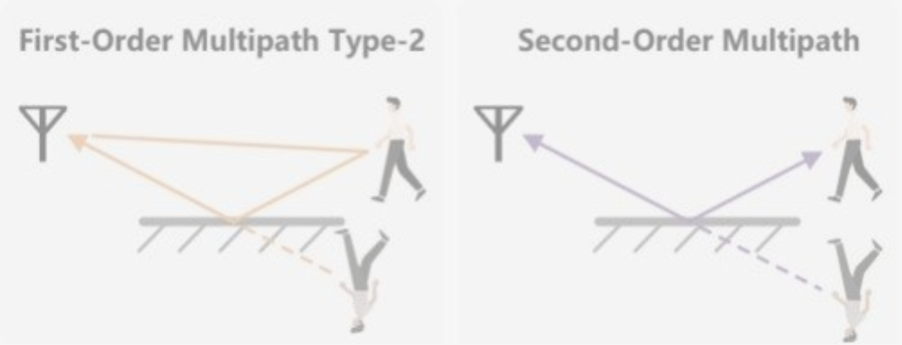
Why Use IMU?

- COTS devices like smartwatch and smartphones
    - So no additional hardware
    - No additional burden on the users
- Helps in easy identity tracking
    - Usually tagged to user's body
- Use existing communication protocols like Bluetooth and WiFi
    - No need of extra hardware
    - Can be streamed to a centralized node for further processing

PmTrack: Challenges

- **Weak Reflection: Results in trajectory loss**
  - Static clutter removal may also remove stationary human data.
  - Obstruction can attenuate the signal.

- **Point Cloud Overlap: Incorrect Tracking Updates**
  - Wrong Segmentation for overlapping positions.
- **Body Bounce Ghost: Interference with real trajectory**
  - False targets created by multipath reflection
  - Majorly caused by first order (type-1) multipath only



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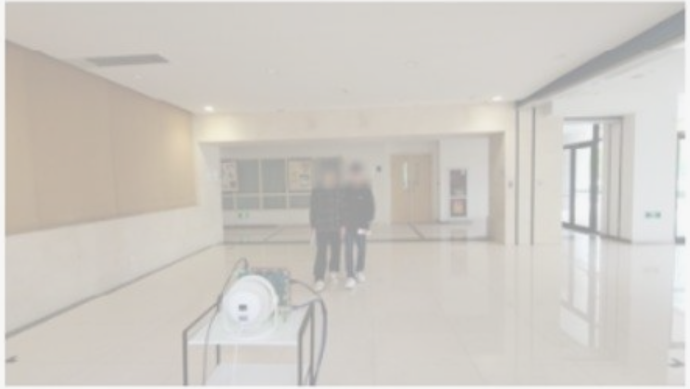

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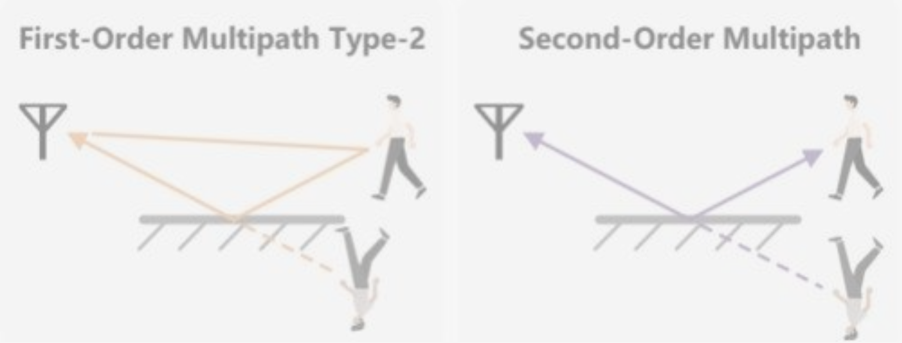

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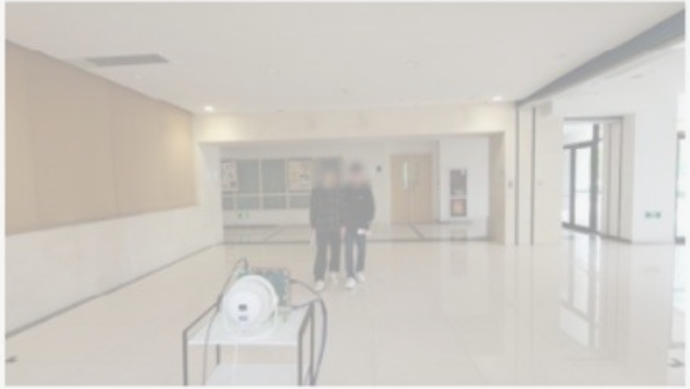

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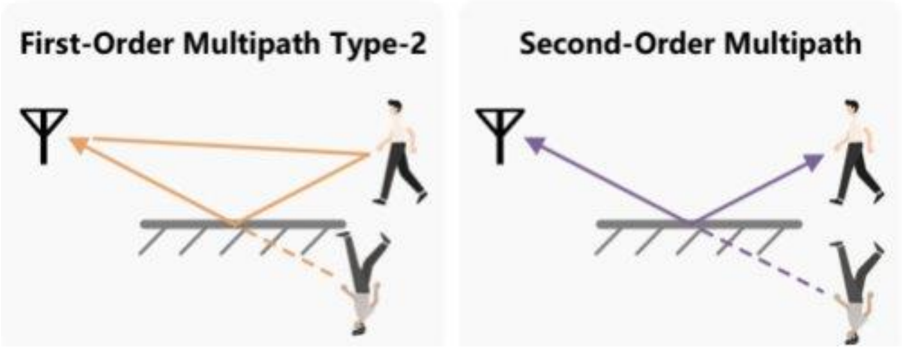
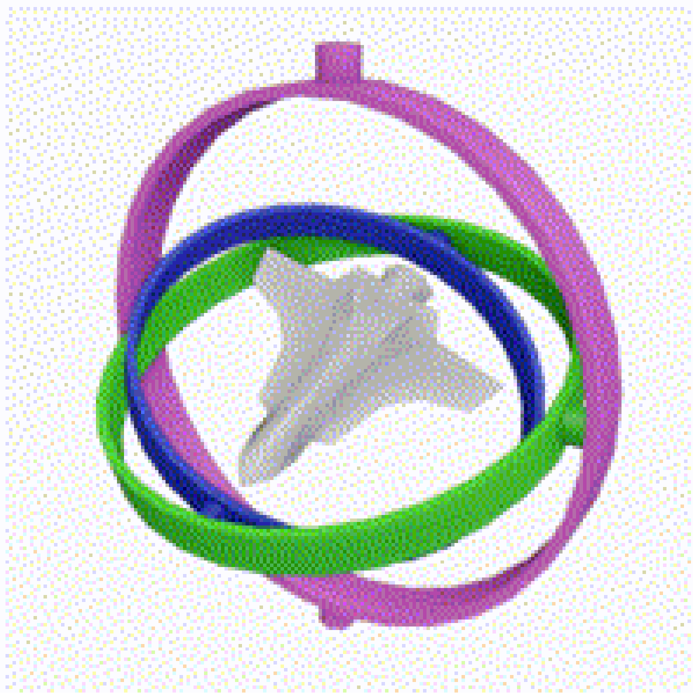
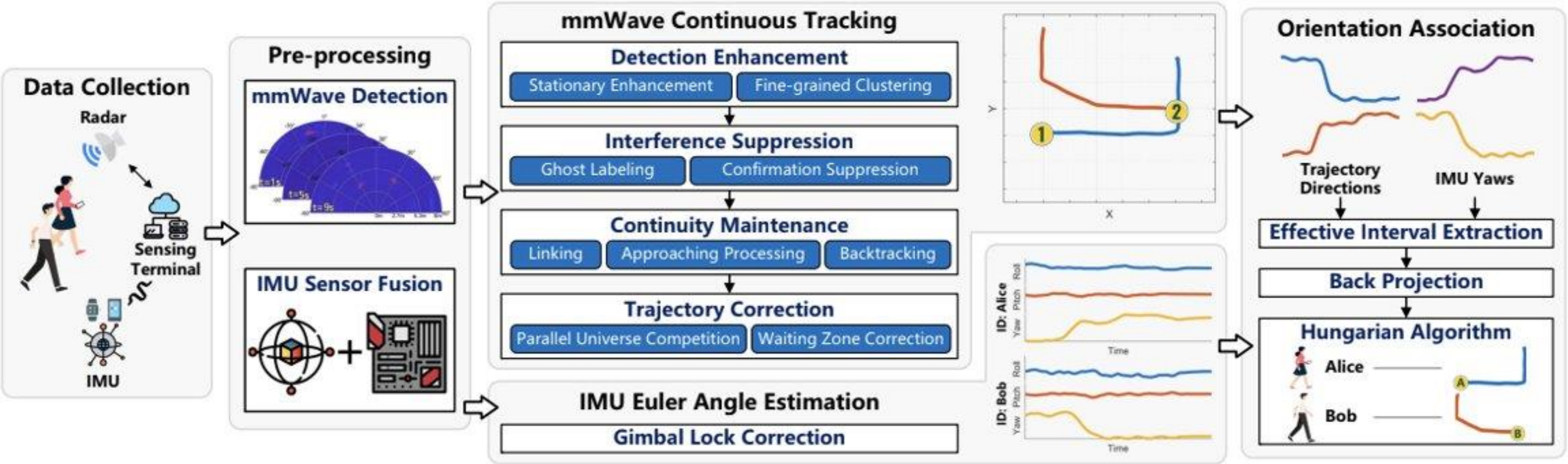


PmTrack: Challenges

- **Gimbal Lock: A scenario when you lose one degree of freedom**
  - When the axis of two of the gimbals become parallel
  - The third axis cannot make any other progress
  - This occurs when the IMU's pitch is near ±90°
  - This makes the yaw and roll axes almost collinear, leading to calculation errors in Euler angles.

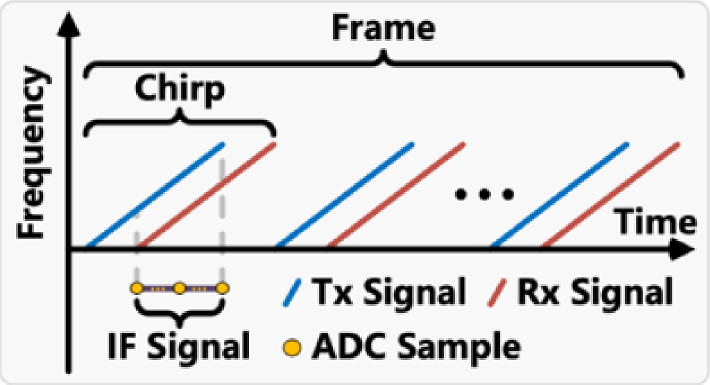


System Overview



Methodology: Data Collection – mmWave Data

- **Radar/Ground Coordinate System**:
  - Radar horizontal plane is parallel to the ground and trajectory orientation
  - Follows right hand screw rule along z-axis
- **mmWave Radar Point Cloud Generation:**
  - FMCW Mechanism:
    - Uses chirp signals with linear increasing frequency
    - Equation of the transmitted signal is given by $s_t(t) = A_t \exp(j2\pi(fc + kt)t)$
    - Equation of the received signal is given by $s_r(t) = \alpha s_t(t-2D(t)/c)$
    - $s(t) = s_t^*(t)s_r(t) \approx A\exp(j4\pi(fc + kt)D(t)/c) = A \exp(j(2\pi f(t)t + \phi(t)))$



FMCW Mechanism

A_t=Starting Amplitude
fc=Starting Frequency
k=Slope
D=Distance
c=Speed of light
φ(t)=Phase offset

For more information:[mmWave Training Series]

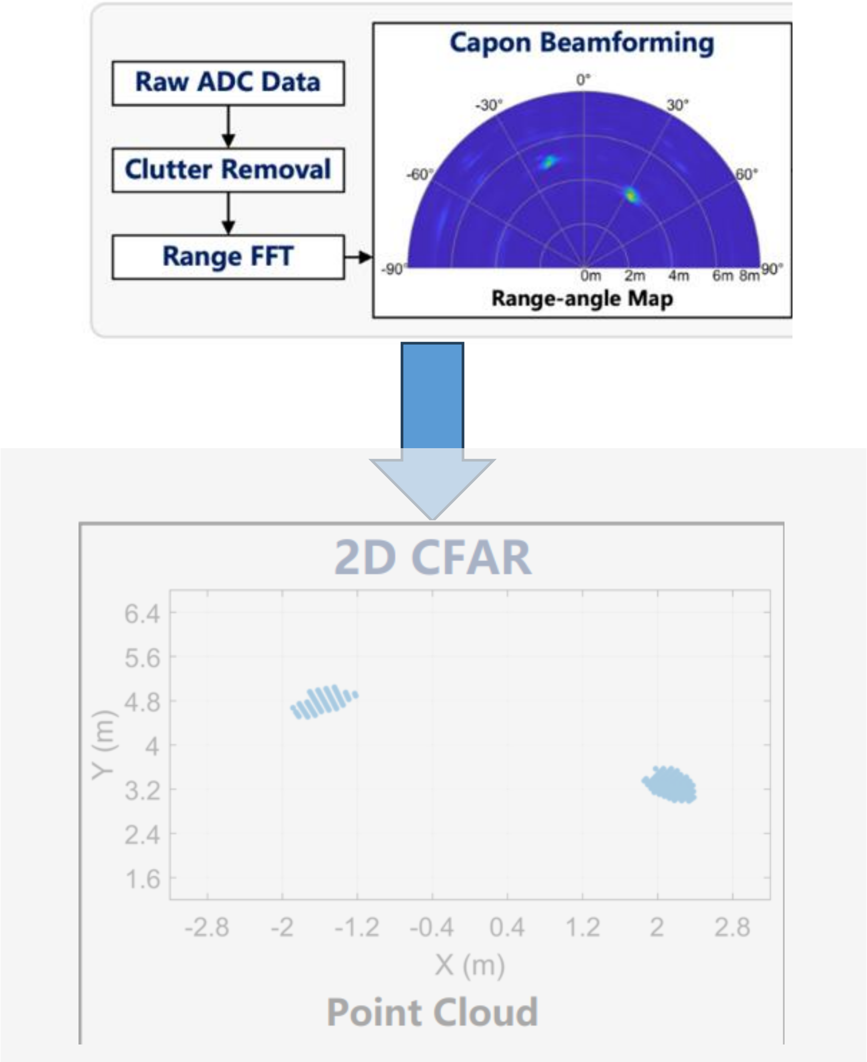
Methodology: Data Collection – IMU Data

- **IMU Coordinate System**:
  - Here the rotation order is z-y-x, x(roll), y(pitch), z(yaw), uses right hand screw rule
  - Yaw describes IMU rotation in the ground coordinate system

- IMU Euler Angle Calculation: 6- axis IMU includes accelerometer and gyroscope
  - Euler angles describes the IMU's attitude with roll, pitch and yaw
  - Utilizes Kalman filter for fusion, quaternion $q=[q_0\ q_1\ q_2\ q_3]$ representation for attitude which are represented as
    - roll = $\mathrm{atan2}(2(q_0q_1 - q_2q_3)\ ,\ 1 - 2(q_1^2 + q_2^2))$
    - pitch = $\mathrm{asin}(2(q_0q_2 + q_1q_3))$
    - yaw = $\boxed{\mathrm{atan2}(2(q_0q_3 - q_1q_2)\ ,\ 1 - 2(q_2^2 + q_3^2))}$

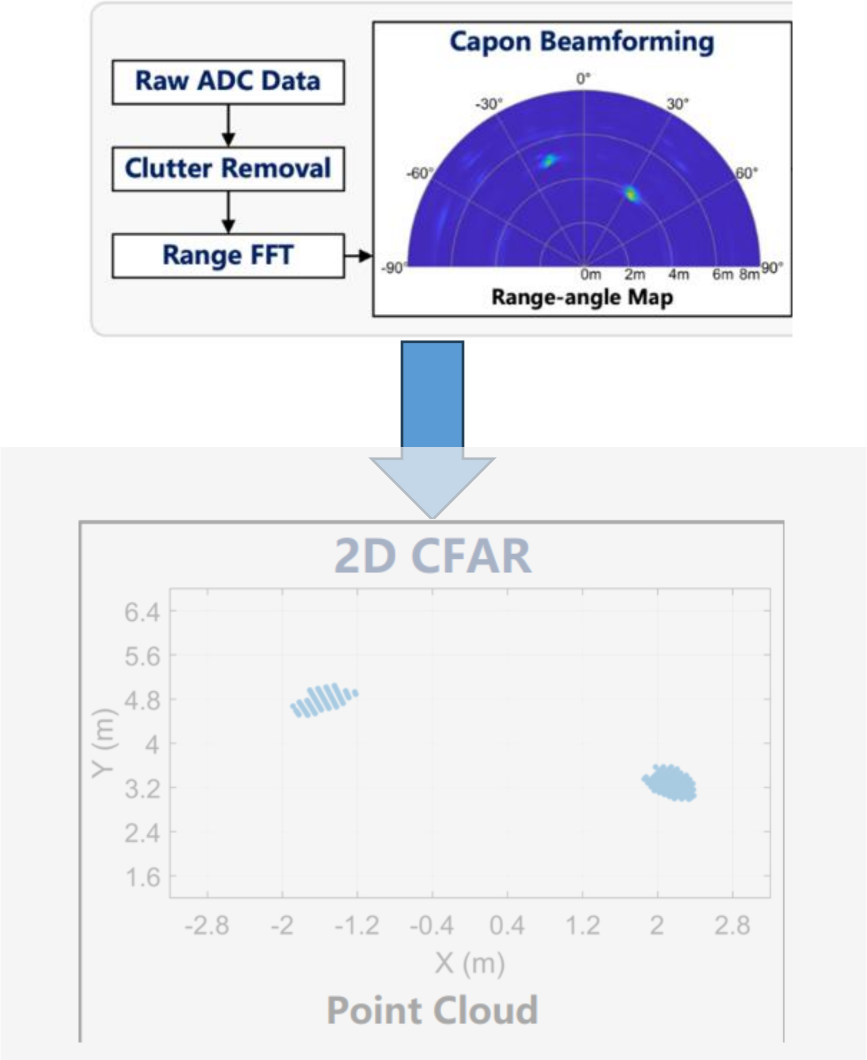
Detailed Methodology: Data Preprocessing

- **Range Detection**:
  - Performed Range FFT to transform signal from time domain to corresponding frequency domain
  - Frequency components correspond to specific distances (Range bins)



Detailed Methodology: Data Preprocessing

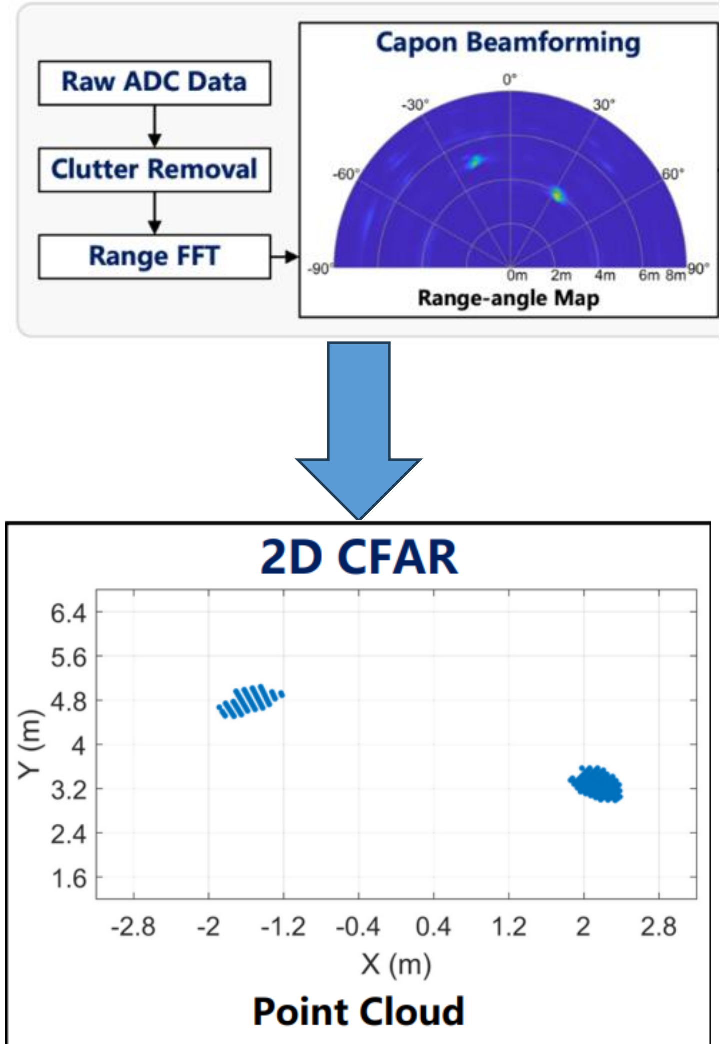
- **Angle Estimation**:
  - Using Capon Beamforming to estimate spatial spectrum by minimizing output power variance
  - Signal strength calculated using $P_{R,\Theta} = 1/ (a_\Theta{}^{H}C_R{}^{-1}a_\Theta)$ and generates range-angle map (RAM)



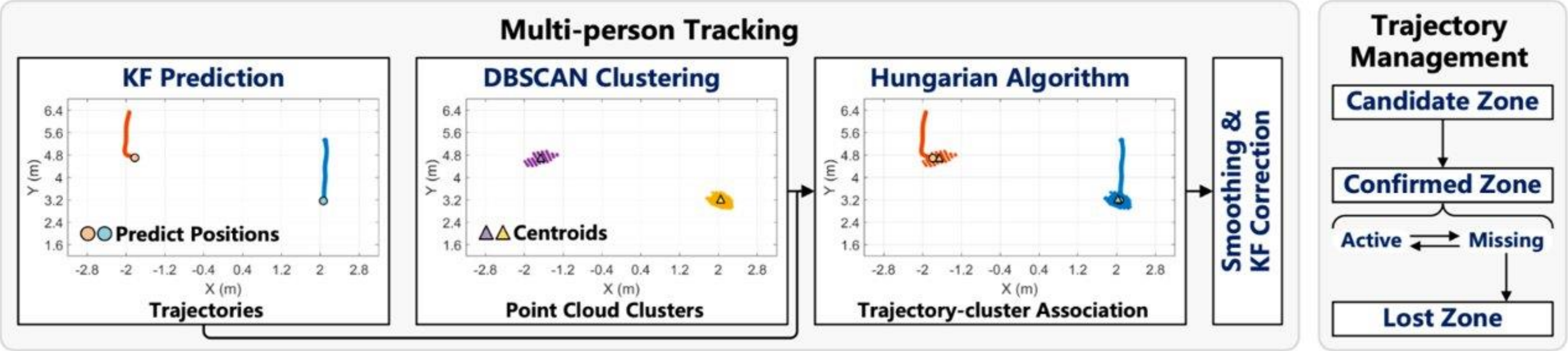
- $P_{R,\Theta}$ is the **received power** at angle Θ.
- a_Θ is the **steering vector** corresponding to angle Θ
- ${}^{H}C_R$ is the **Hermitian transpose** (complex conjugate transpose) of the steering vector.

Detailed Methodology: Data PreProcessing

- **Target Detection**:
  - Uses CA-CFAR (Cell Averaging Constant False Alarm Rate) algorithm to generate 2D window around each RA bin.
    - A false alarm occurs when the algorithm detects a target where there is none (due to noise or clutter)
    - Aims to maintain a constant false alarm rate, meaning it adjusts the detection threshold so that the probability of false detections remains stable, even in varying noise or clutter environments.

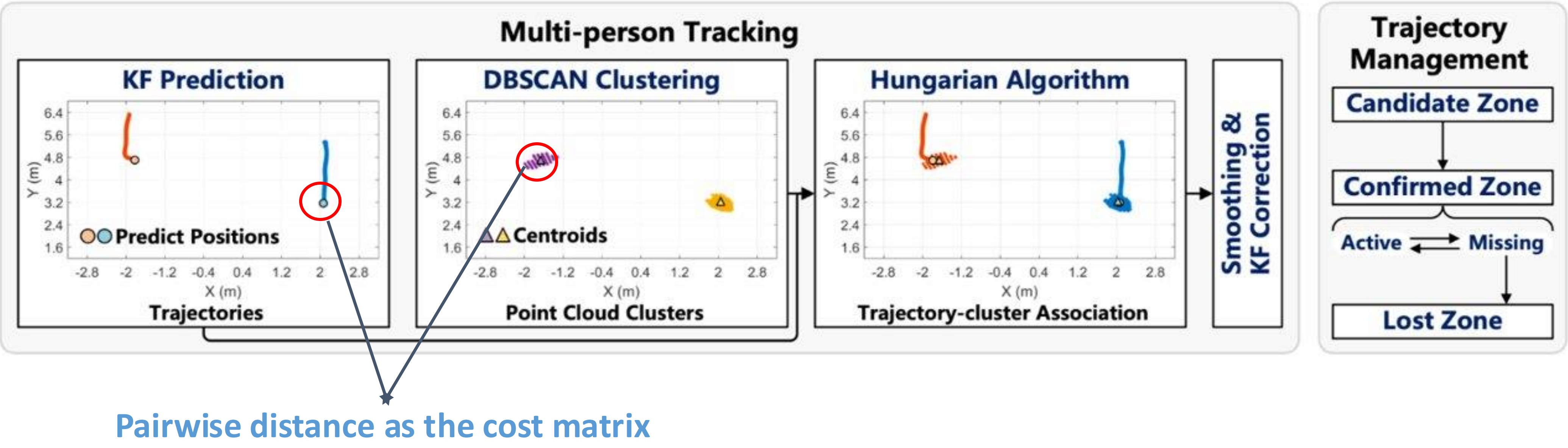


Detailed Methodology: Trajectory Prediction and Correction



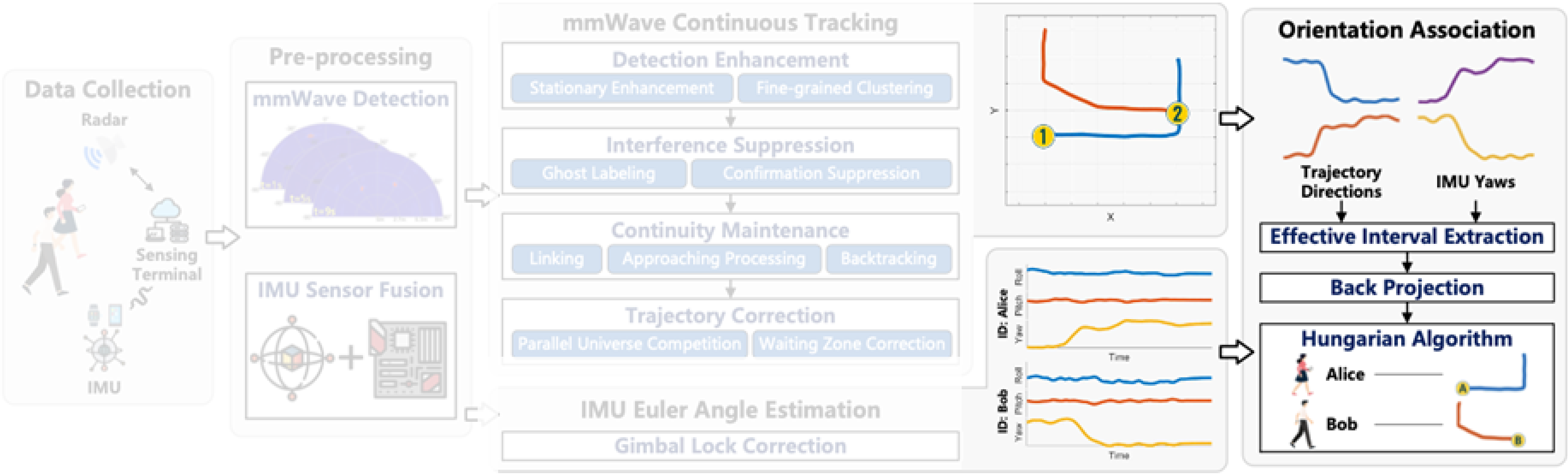
- **Kalman Filter (KF)** is used for **trajectory prediction** and **correction** in a **constant velocity model**
- The **DBSCAN** algorithm is used for clustering when the number of people is unknown.

Detailed Methodology: Trajectory Prediction and Correction



- Now we associate the already present trajectory with the new centroids
- The distance between each **trajectory-centroid** pair is given as cost to the Hungarian algorithm
- The algorithm solves this **bipartite graph** problem by finding **optimal associations** based on a **distance threshold**.

Orientation Association

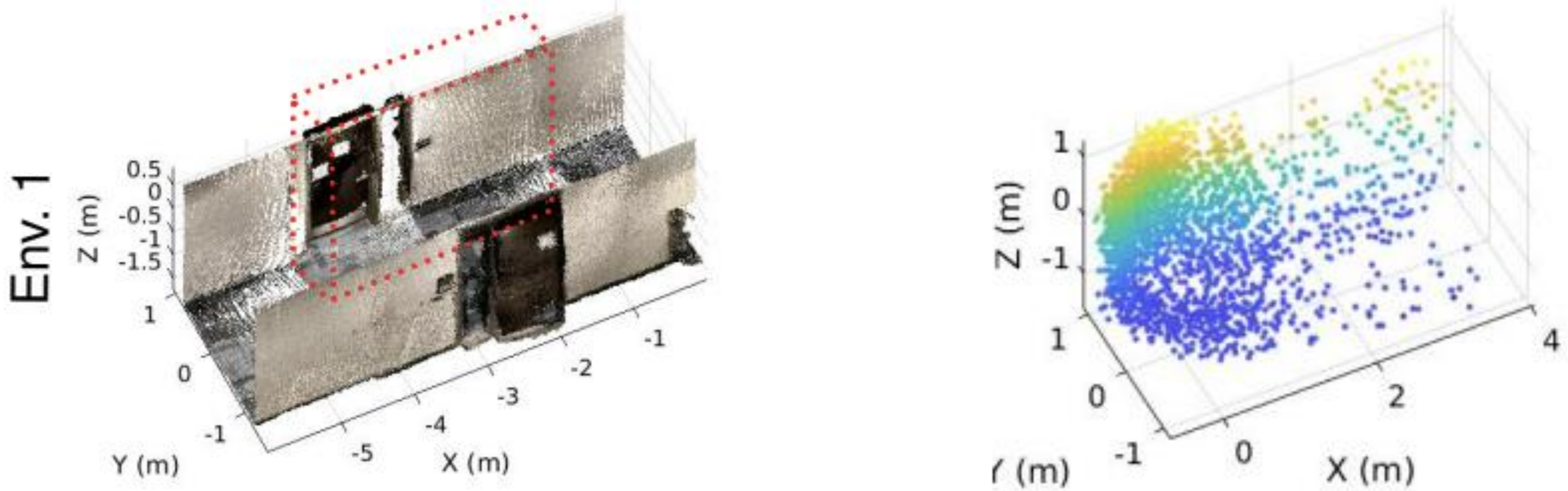


- **Orientation Measurement:**
  - Trajectory orientation: Calculated using a 0.5s moving time window
  - IMU orientation: Uses yaw, filtered through a 1s moving window
    - Aligned with trajectory orientation using linear interpolation

Summary

- RF Sensing is a powerful method for ubiquitous computing to monitor moving subjects and their movement patterns

- Even, there are applications beyond moving subjects



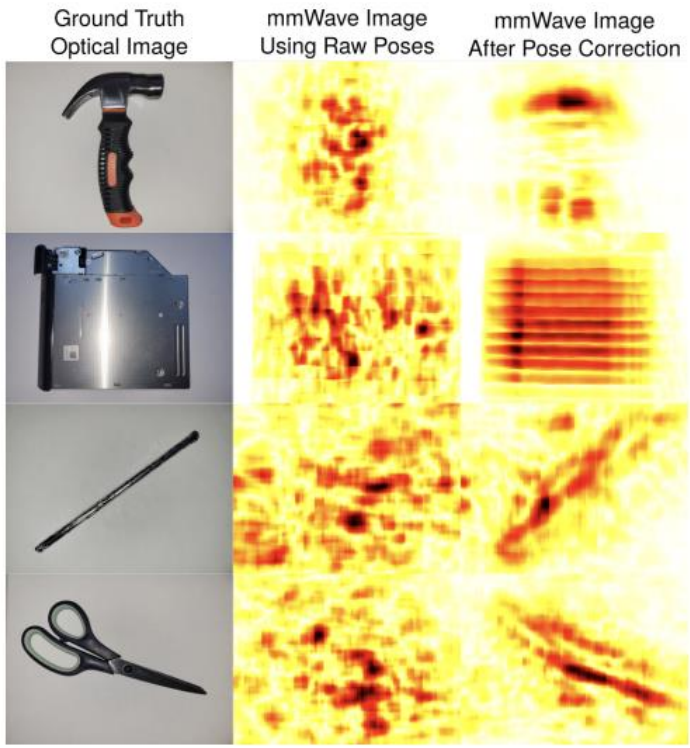
3D PCD for an Indoor Structure

Summary

- RF Sensing is a powerful method for ubiquitous computing to monitor moving subjects and their movement patterns

- Even, there are applications beyond moving subjects

Imaging of handheld devices



Happy Learning!

Some resources related to this topic