6G通訊與感測研究中心
6G Communication and Sensing Research Center

2025
R&S Wireless Innovation Day
Unlock what's possible
Unveil technologies sustainable

4D MIMO Radar Technologies Enabling ISAC in B5G/6G Systems

T.-S. Jason Horng
Department of Electrical Engineering
National Sun Yat-Sen University
Kaohsiung, Taiwan

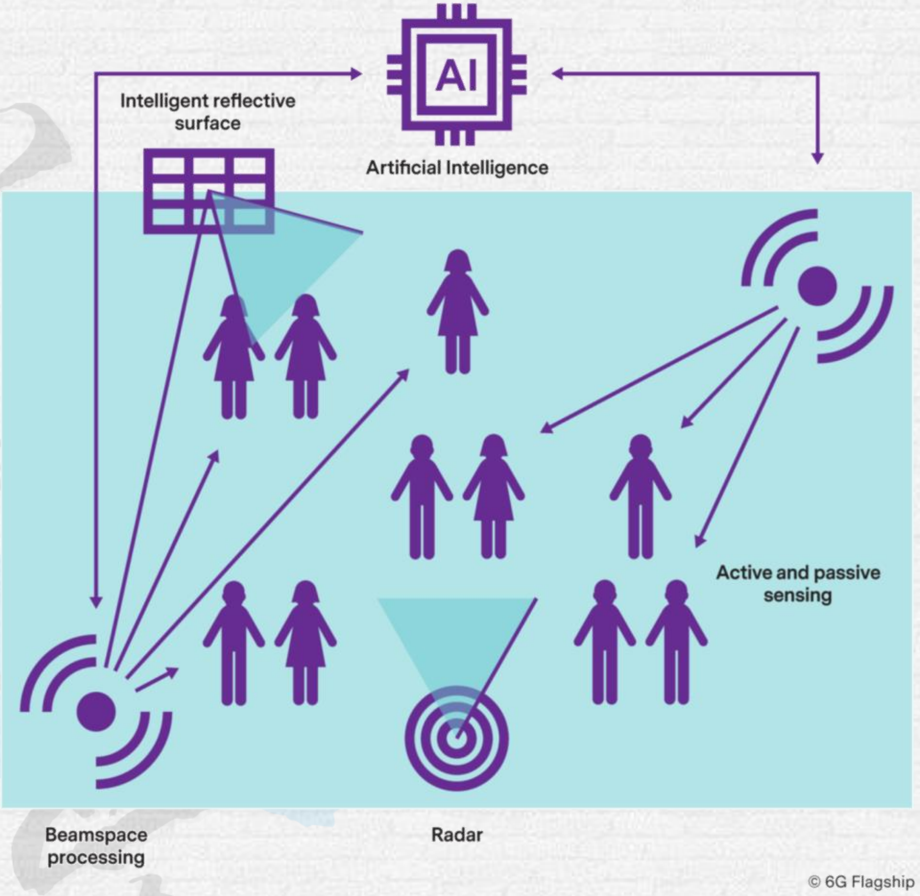
June 24, 2025

Outline

- Opportunities and Challenges of Integrated Sensing and Communication (ISAC) Systems
- Fundamental Sensing Technologies: Radar + MIMO + CSI
- Monostatic ISAC Scenarios Enabled by 4D Radar
  - MIMO Passive Radar Leveraging Base Station CSI
  - MIMO Passive Radar Utilizing Repeater Signals
  - MIMO Active Radar Driven by Cognitive Sensing
- Conclusions

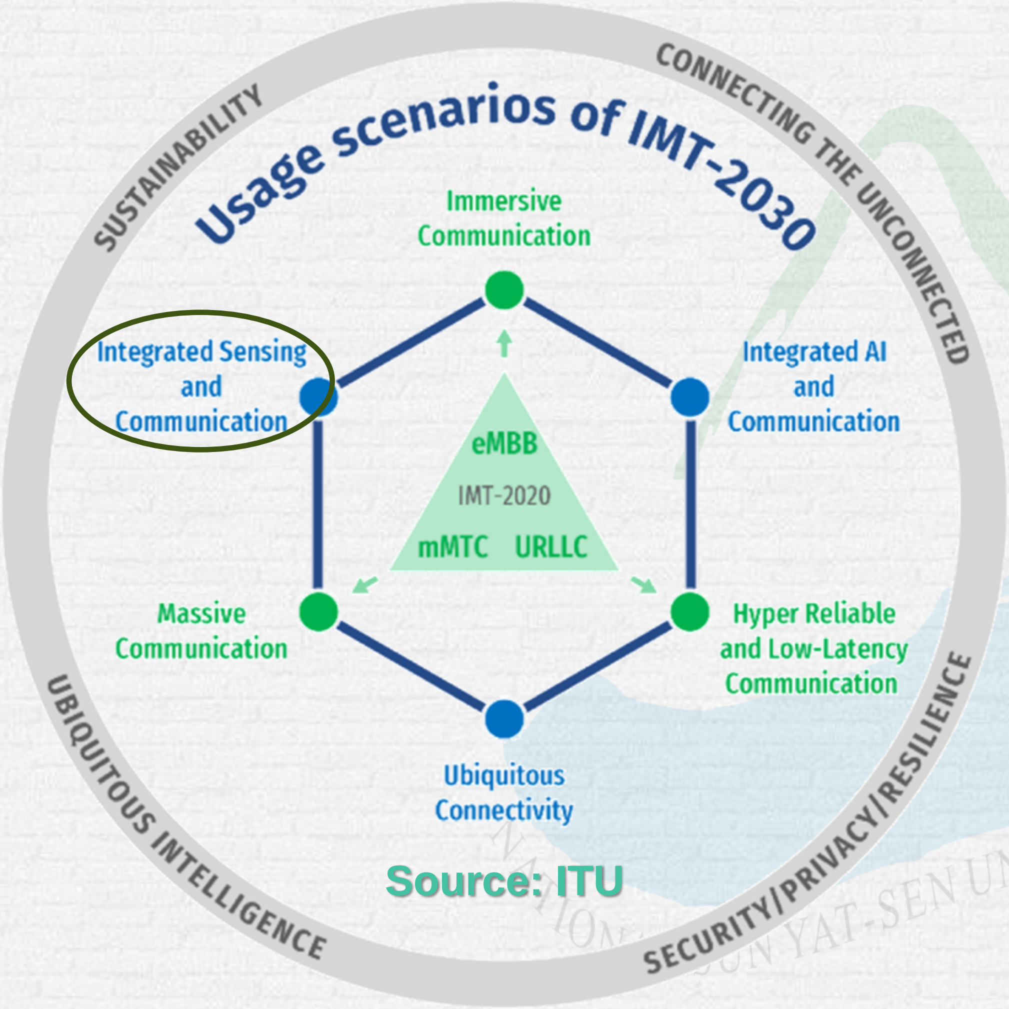
Localization and Sensing in 6G Networks

- Environment-aware communication systems
  - RF spectrum for localization and sensing systems
  - Intelligent reflective surfaces for mapping and localization
  - Beamspace processing for accurate positioning
  - Machine learning for intelligent localization and sensing
- Localization and sensing opportunities
  - Simultaneous localization and mapping
  - Passive sensing using transmitters of opportunity
  - Active sensing with radar and communications convergence
  - Context-aware localization systems



Source: University of Oulu, 6G White Paper on Localization and Sensing, 2020

Integrated Sensing & Communication (ISAC)



Source: ITU

5G Towards 6G

ISAC involves scenarios where the communication system provides sensing services (communication-assisted sensing) and where environmental sensing information is used to improve the communication service of the system itself (sensing-assisted communication).

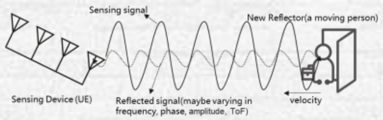
Source: Study on Integrated Sensing and Communication (Release 19), 3GPP SP-220717 (2022-06)

Use Cases

Index	Use Case	Index	Use Case
1	Intruder detection in smart home	17	Health monitoring at home
2	Pedestrian/animal intrusion detection on a highway	18	Service continuity of unobtrusive health monitoring
3	Rainfall monitoring	19	Sensor Groups
4	Transparent Sensing Use Case	20	Sensing for Parking Space Determination
5	Sensing for flooding in smart cities	21	Seamless XR streaming
6	Intruder detection in surroundings of smart home	22	UAVs/vehicles/pedestrians detection near Smart Grid equipment
7	Sensing for railway intrusion detection	23	AMR collision avoidance in smart factories
8	Sensing Assisted Automotive Maneuvering and Navigation	24	Roaming for sensing service of sports monitoring
9	AGV detection and tracking in factories	25	Immersive experience based on sensing
10	UAV flight trajectory tracing	26	Accurate sensing for automotive maneuvering and navigation service
11	Sensing at crossroads with/without obstacle	27	Public safety search and rescue or apprehend
12	Network assisted sensing to avoid UAV collision	28	Vehicles Sensing for ADAS
13	Sensing for UAV intrusion detection	29	Gesture Recognition for Application Navigation and Immersive Interaction
14	Sensing for tourist spot traffic management	30	Sensing for automotive maneuvering and navigation service when not served by RAN
15	Contactless sleep monitoring service	31	Blind spot detection
16	Protection of Sensing Information	32	Integrated sensing and positioning in factory hall

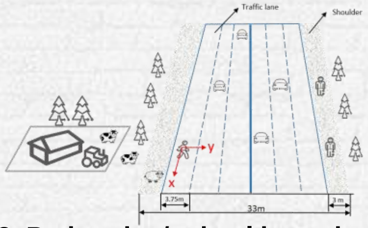
Source: Feasibility Study on Integrated Sensing and Communication (Release 19), 3GPP TR-22.837 (2023-06)

Human Sensing

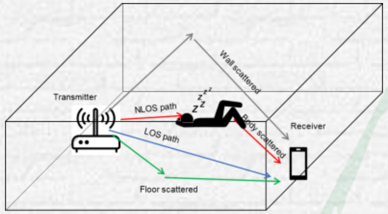


1. Intruder detection in smart home

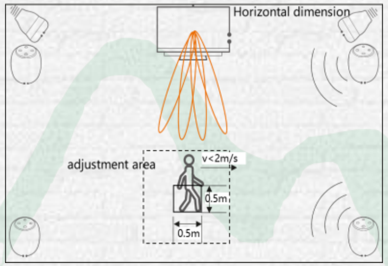
14. Sensing for tourist spot traffic management



2. Pedestrian/animal intrusion detection on a highway

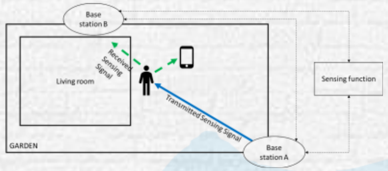


15. Contactless sleep monitoring service

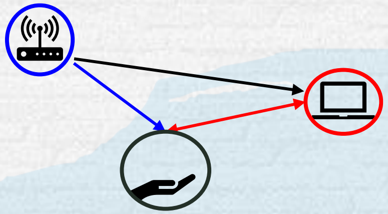


25. Immersive experience based on sensing

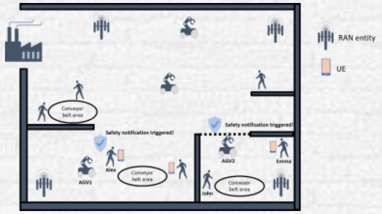
7. Sensing for railway intrusion detection



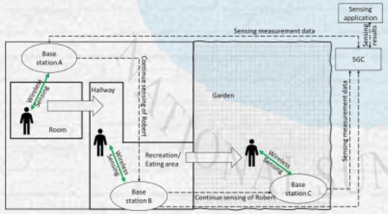
17. Health monitoring at home



29. Gesture Recognition for Application Navigation and Immersive Interaction



9. AGV detection and tracking in factories



18. Service continuity of unobtrusive health monitoring

Table x. Evaluation parameters for Human (indoor and outdoor) sensing scenarios

Parameters		Indoor Values	Outdoor Values
Applicable communication scenarios NOTE1		Indoor office, indoor factory [TR38.901] Indoor room [TR38.808]	UMi, Uma, RMa [TR38.901]
Sensing transmitters and receivers properties	Rx/Tx Locations NOTE 2	Rx/Tx locations are selected among the TRPs and UE locations in the corresponding communication scenario	Rx/Tx locations are selected among the TRPs and UE locations in the corresponding communication scenario
	Rx/Tx Mobility for UEs	Option 1: 0km/h Option 2: 3km/h Option 3: Uniform distribution between 0km/h and 3km/hr	Option 1: 0km/h Option 2: 3km/h Option 3: Uniform distribution between 0km/h and 10km/hr
Sensing target	Outdoor/indoor	Indoor	Outdoor
	3D mobility	Option 1: 0km/h Option 2: 3km/h Option 3: Uniform distribution between 0km/h and 3km/hr (horizontal plane with random direction straight-line trajectory)	Option 1: 0km/h Option 2: 3km/h Option 3: Uniform distribution between 0km/h and 10km/hr (horizontal plane with random direction straight-line trajectory)
	3D distribution	N targets uniformly distributed over the horizontal area of the convex hull of the TRP deployment FFS: Value of N	Uniform in horizontal plane
	Orientation	Random over the horizontal area	Random over the horizontal area
	Physical characteristics (e.g., size)	Size (Length x Width x Height): - Child: 0.2m x 0.3m x 1m - Adult Pedestrian: 0.5m x 0.5m x 1.75m	Size (Length x Width x Height): - Child: 0.2m x 0.3m x 1m - Adult Pedestrian: 0.5m x 0.5m x 1.75m
Minimum 3D distances between pairs of Tx/Rx and sensing target		Option 1: Min. distance is larger than the min. far-field distance of the sensing Tx/Rx Option 2: Min distances defined in TR 38.901 as a starting point	Option 1: Min. distance is larger than the min. far-field distance of the sensing Tx/Rx Option 2: Min distances defined in TR 38.901 as a starting point
Minimum 3D distance between sensing targets		Option 1: At least larger than the physical size of a sensing target Option 2: Fixed value, [x] m. value of x is FFS	Option 1: At least larger than the physical size of a sensing target Option 2: Fixed value, [x] m. value of x is FFS
Environment Objects, e.g., types, characteristics, mobility, distribution, etc.		FFS, based on outcome for AI 9.7.2	FFS, based on outcome for AI 9.7.2

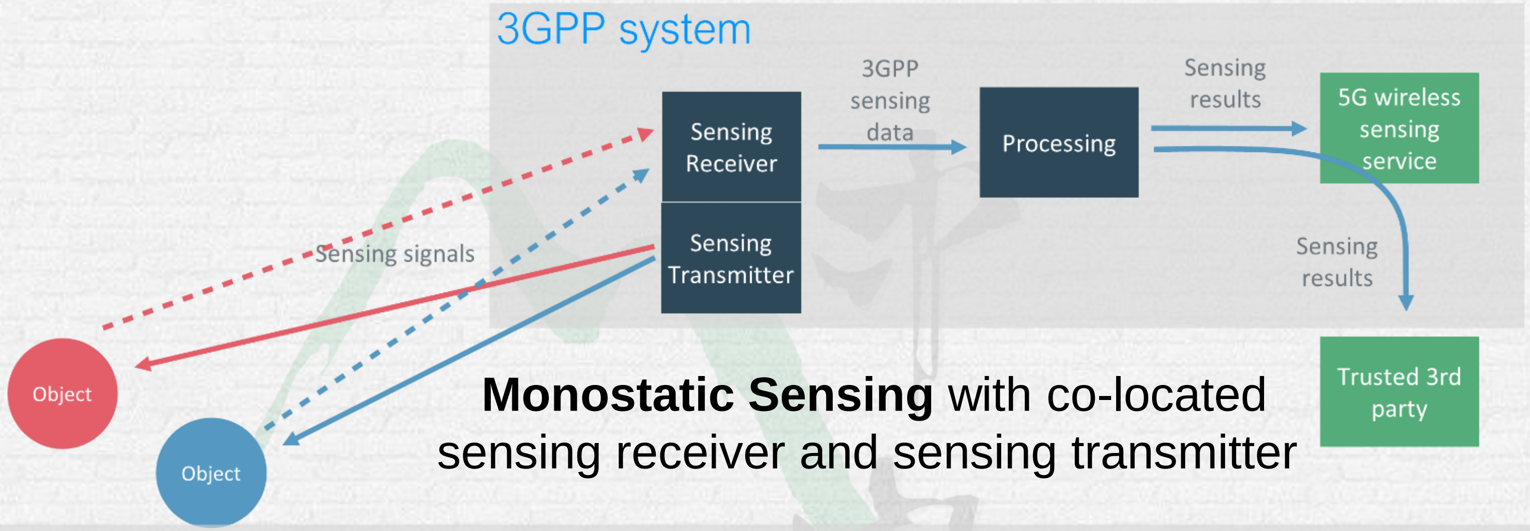
Source: ISAC Deployment Scenarios (Release 19), 3GPP RP-242804 (2024-12)

Key Performance Indicators

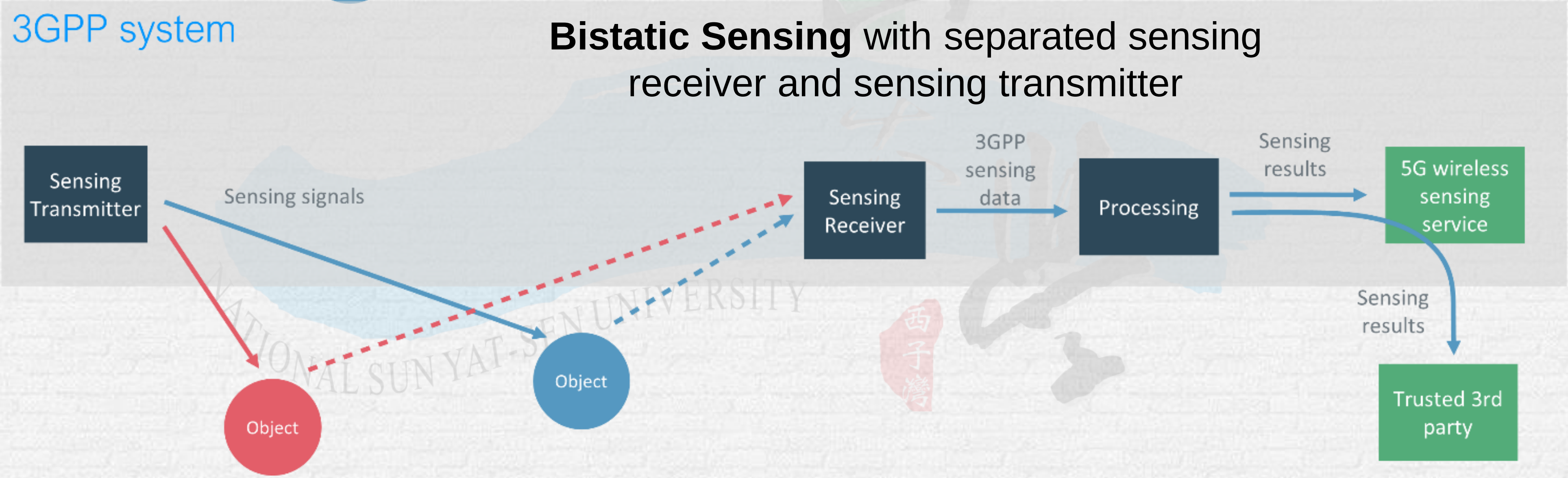
Scenario	Sensing service category	Confidence level [%]	Accuracy of positioning estimate by sensing (for a target confidence level)		Accuracy of velocity estimate by sensing (for a target confidence level)		Sensing resolution		Max sensing service latency [ms]	Refreshing rate [s]	Missed detection [%]	False alarm [%]	Sensing service description in a target sensing service area
			Horizontal [m]	Vertical [m]	Horizontal [m/s]	Vertical [m/s]	Range resolution [m]	Velocity resolution (horizontal/ vertical) [m/s x m/s]					
Object detection and tracking	1	95	10	10	N/A	N/A	10 [3]	5 [3]	1000	1	5	2	Indoor/outdoor (e.g., detection of human, UAV)
	2	95	2	5	1	N/A	1	1	1000	0.2	0.1 to 5	5	Outdoor (e.g., detection of human, UAV)
	3	95	1	1	1 [3], [4]	1	1 [3], [4]	1 x 1 [3]	100 [2], or 1000 (NOTE 3); 5000 for detection in highway	0.05 to 1	2	2	Indoor/outdoor (e.g., detection and tracking of human, animal, UAV)
	4	99 for public safety, otherwise, 95	0.5	0.5	1.5 for pedestrian, 15 for vehicle, otherwise, 0.1	1.5 for pedestrian	0.5	0.5 x 0.5 for factories	100 to 5000	0.1	1	3	Indoor/outdoor (e.g., detection and tracking of human, animal, UAV, AGV, vehicle) requiring higher performance than category 3
Environment monitoring	5	95	10	0.2 (NOTE 4)	N/A	N/A	N/A	N/A	60000	60 to 600	0.1 to 5	3	Nature of environments monitored by sensing (e.g. rainfall, flooding monitoring)
Motion monitoring	6	95	N/A	N/A	N/A	N/A	N/A	N/A	60000	60	5	5	Human motions and activities obtained by sensing (NOTE 5)
	7	95	0.2	0.2	0.1	0.1	0.375	0.3	5 to 50	0.1	5	5	Human hand gestures obtained by sensing (NOTE 6)

Source: Service Requirements for Integrated Sensing and Communication, (Release 19), 3GPP TS-22.137 (2023-12)

Sensing Configuration



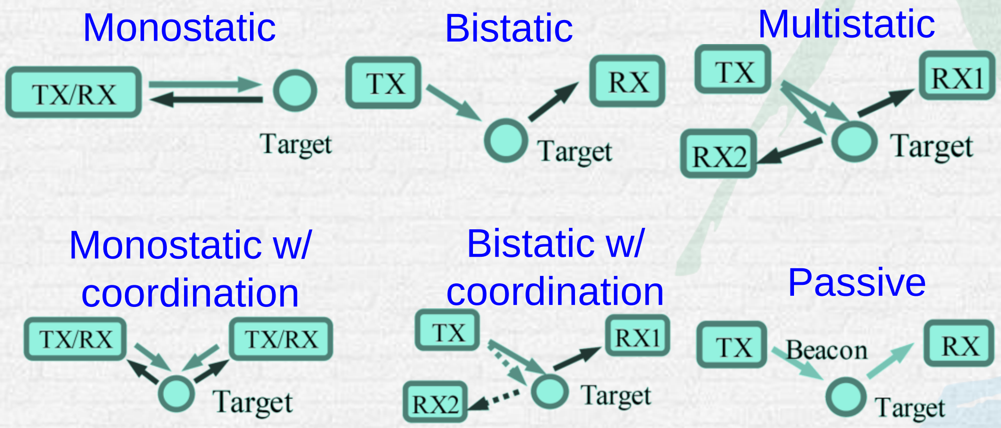
Monostatic Sensing with co-located sensing receiver and sensing transmitter



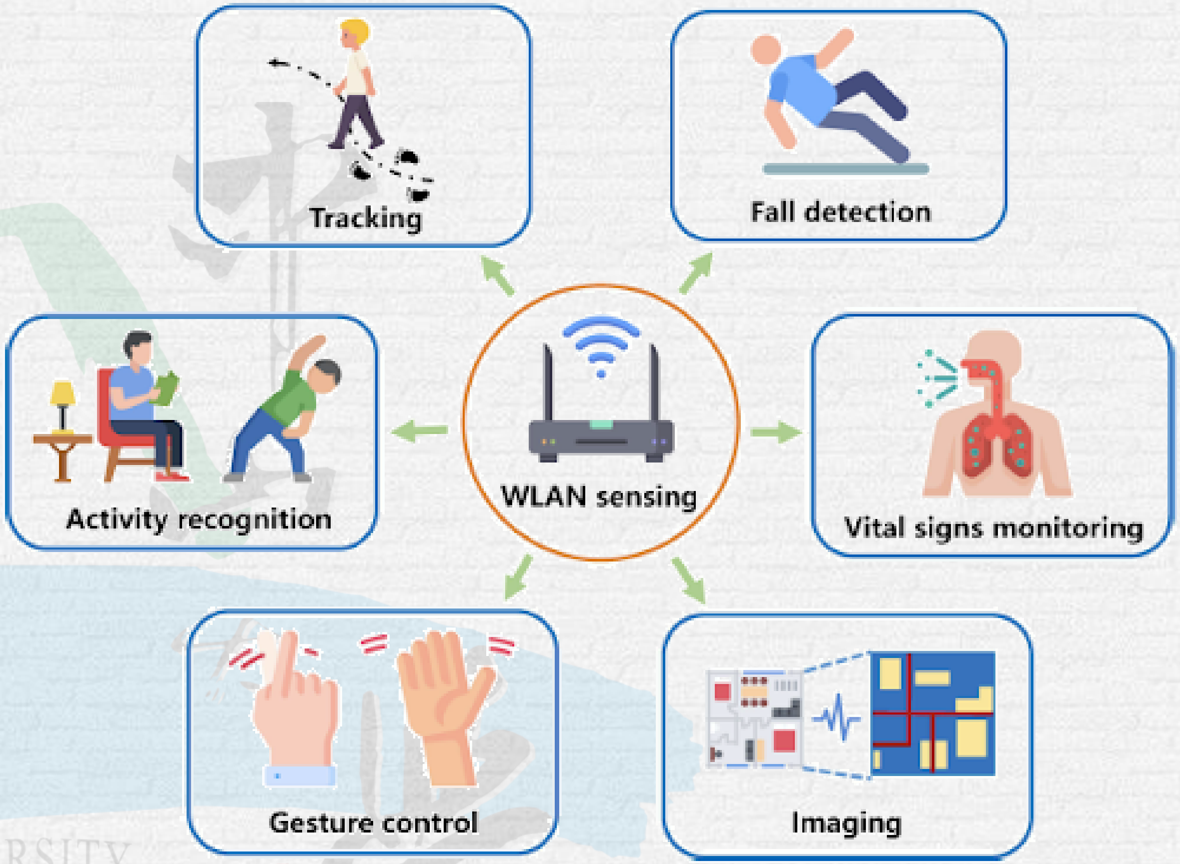
Bistatic Sensing with separated sensing receiver and sensing transmitter

Source: Service requirements for Integrated Sensing and Communication, (Release 19), 3GPP TS-22.137 (2023-12)

Wi-Fi Sensing



Sensing Modes

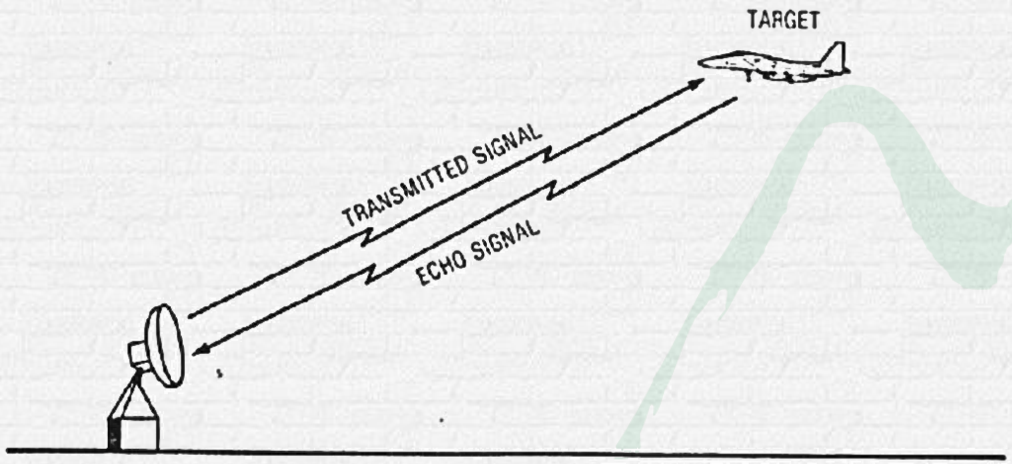


Sensing Applications

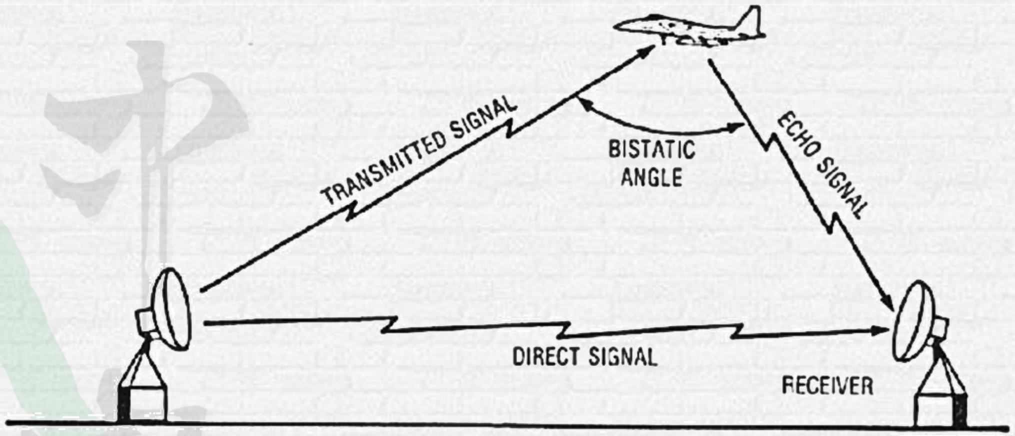
Source: Chinese University of Hong Kong (2023)

IEEE 802.11bf, the Wi-Fi sensing standard, began in 2020 and will be finalized in 2025.

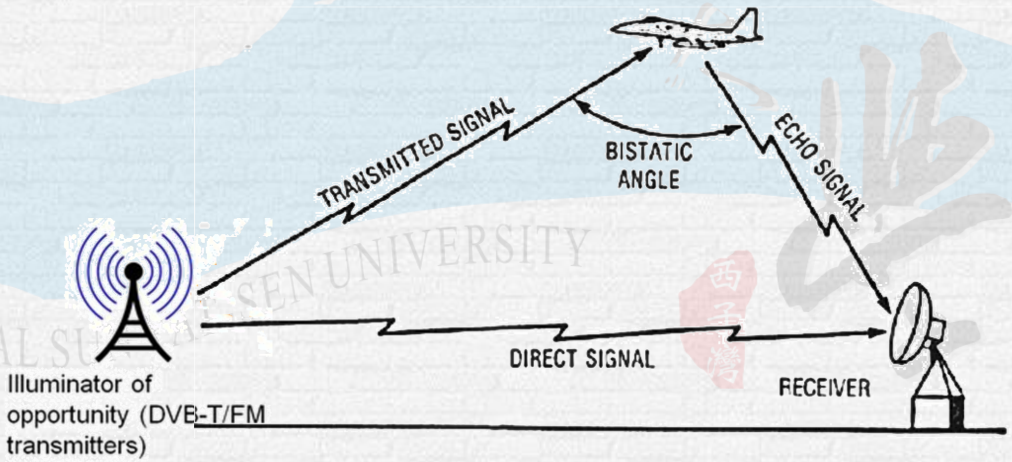
Radar Systems



Monostatic Radar



Bistatic Radar

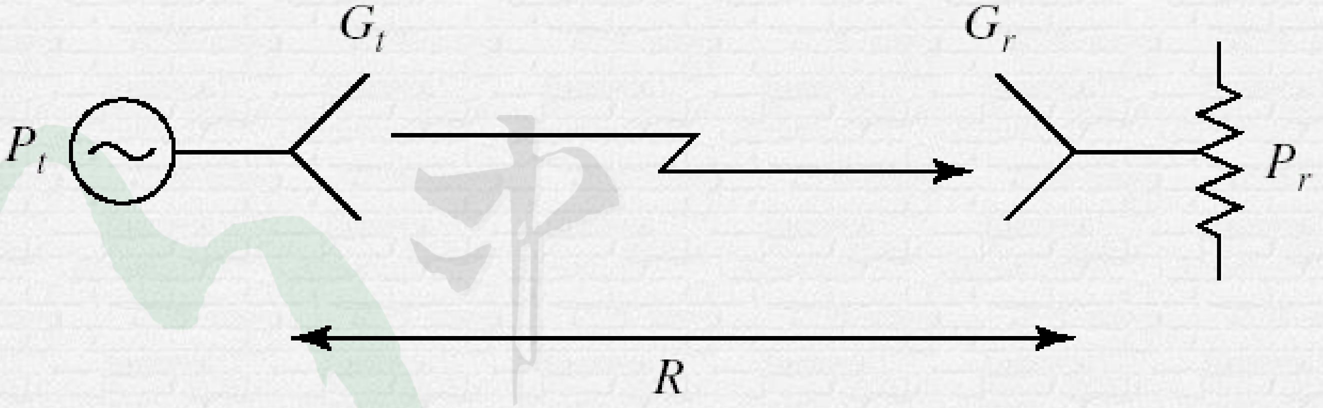


Passive Radar

Coverage Issue

Friis Formula

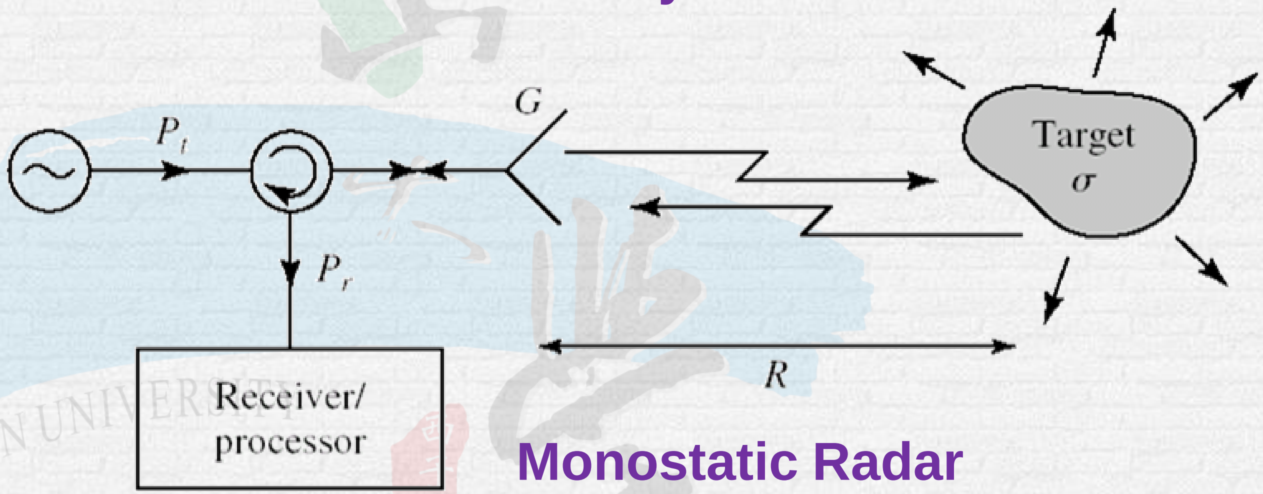
$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t$$



Radio System

Radar Equation

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

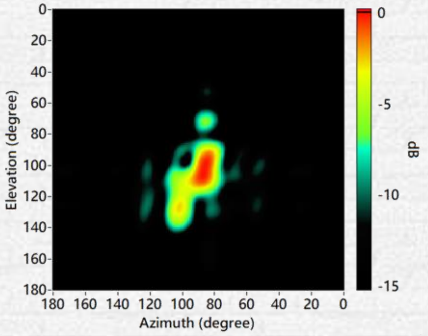


Monostatic Radar

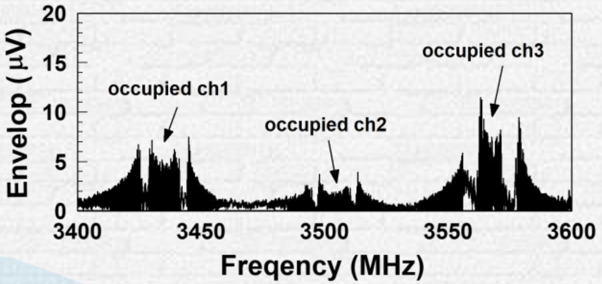
A simple guideline is that if the effective communication range is R, the sensing range will be $\sqrt{R}$.

Cognitive Sensing

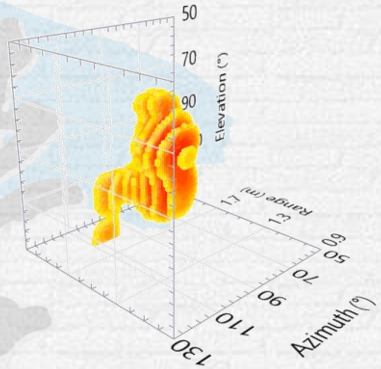
Use **Passive Sensing** to monitor the channel environment in real time and identify the target of interest.



Perform **Spectrum Sensing** to find available channels.

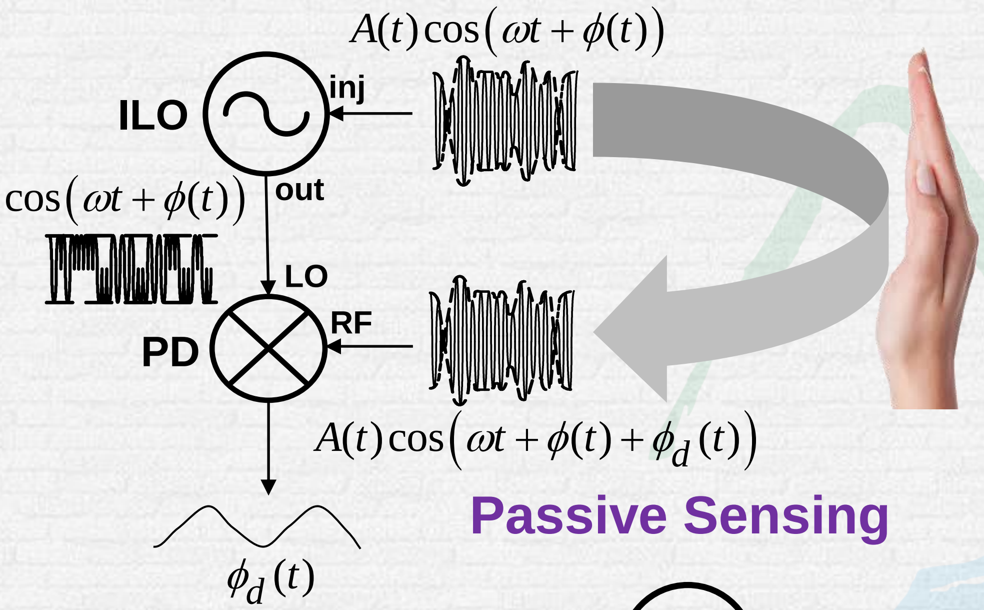


Apply **Active Sensing** to track the target of interest in real time through the available channels.

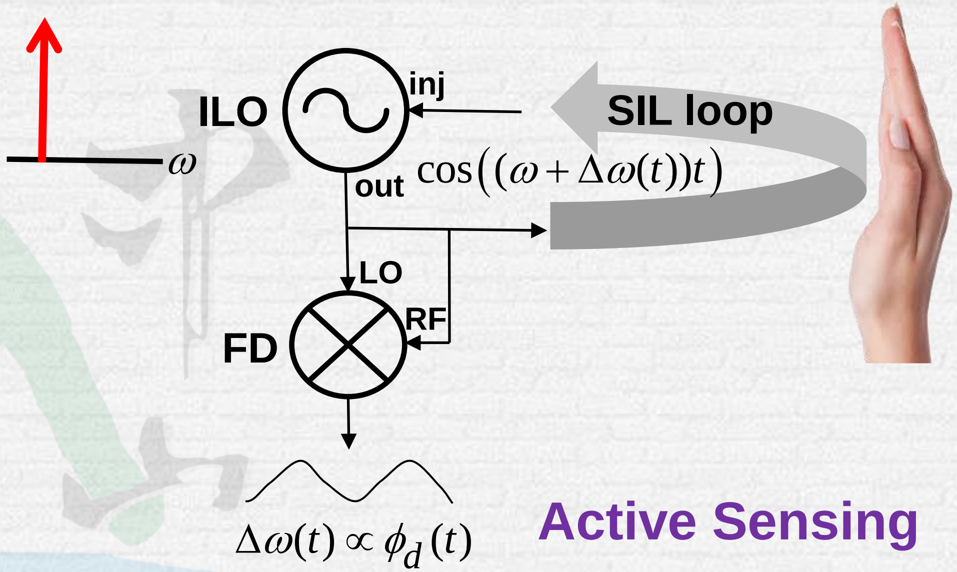


Active sensing offers a higher SNR and greater bandwidth than passive sensing, enhancing both sensitivity and resolution and ultimately delivering a higher QoS.

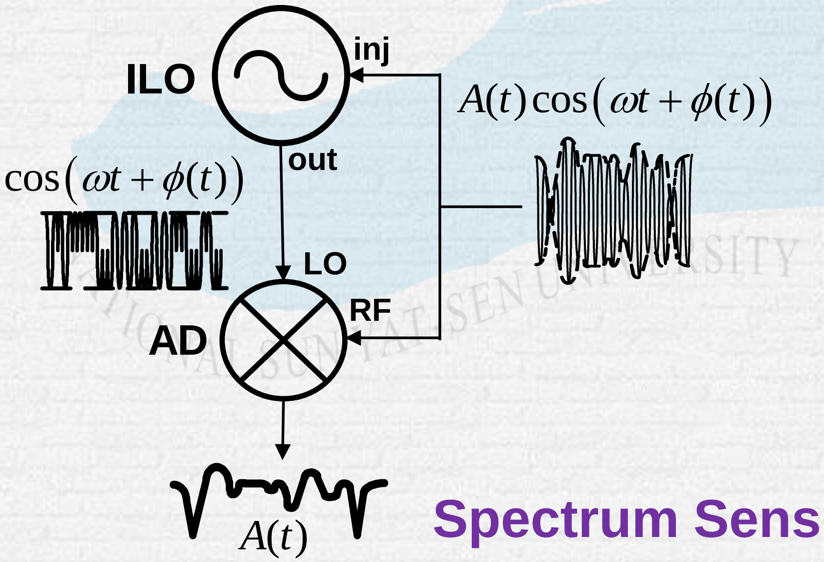
Injection-Locked Oscillator (ILO)-Based Sensing



Passive Sensing



Active Sensing



Spectrum Sensing

ILO: Injection-**L**ocked **O**scillator

PD: Phase **D**etector

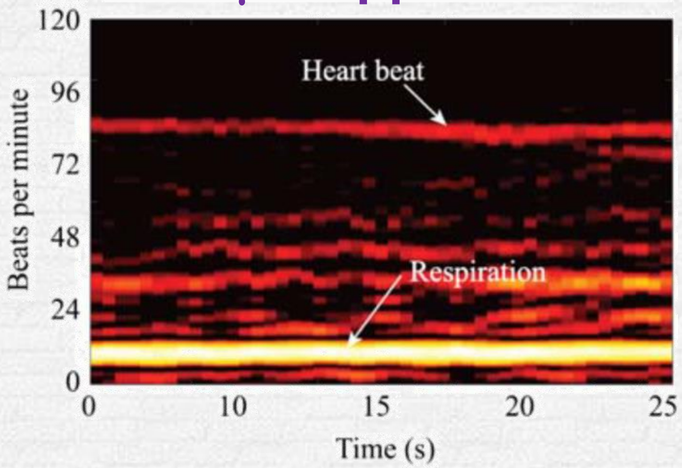
FD: Frequency **D**etector

AD: Amplitide **D**etector

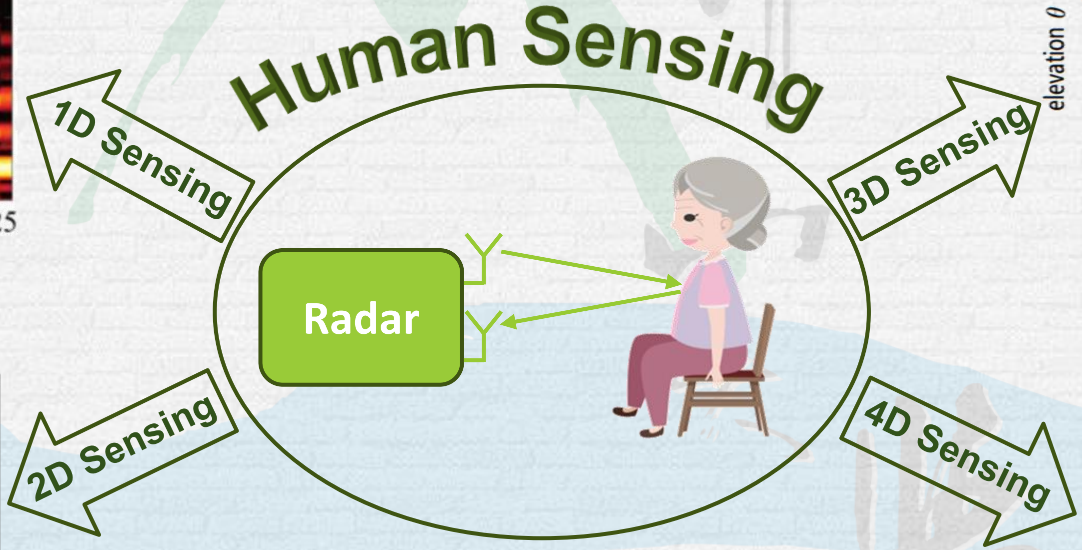
SIL: Self-**I**njection-**L**ocking

Multi-dimensional Sensing

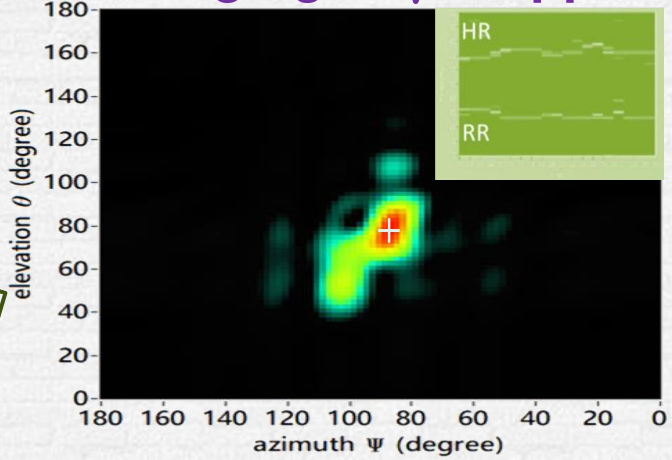
μ-Doppler



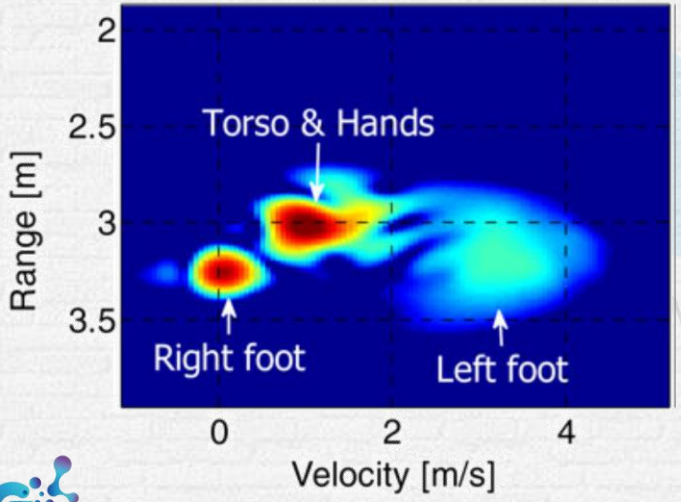
The μ-Doppler map reveals the target's instantaneous motion and vital sign frequencies.



2D Imaging w/ μ-Doppler

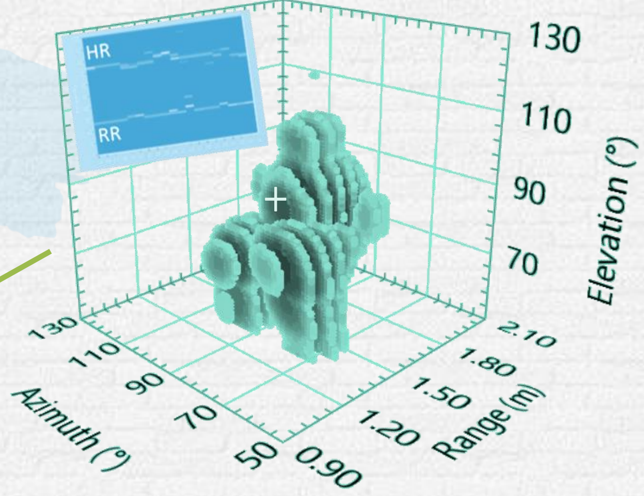


Range Doppler

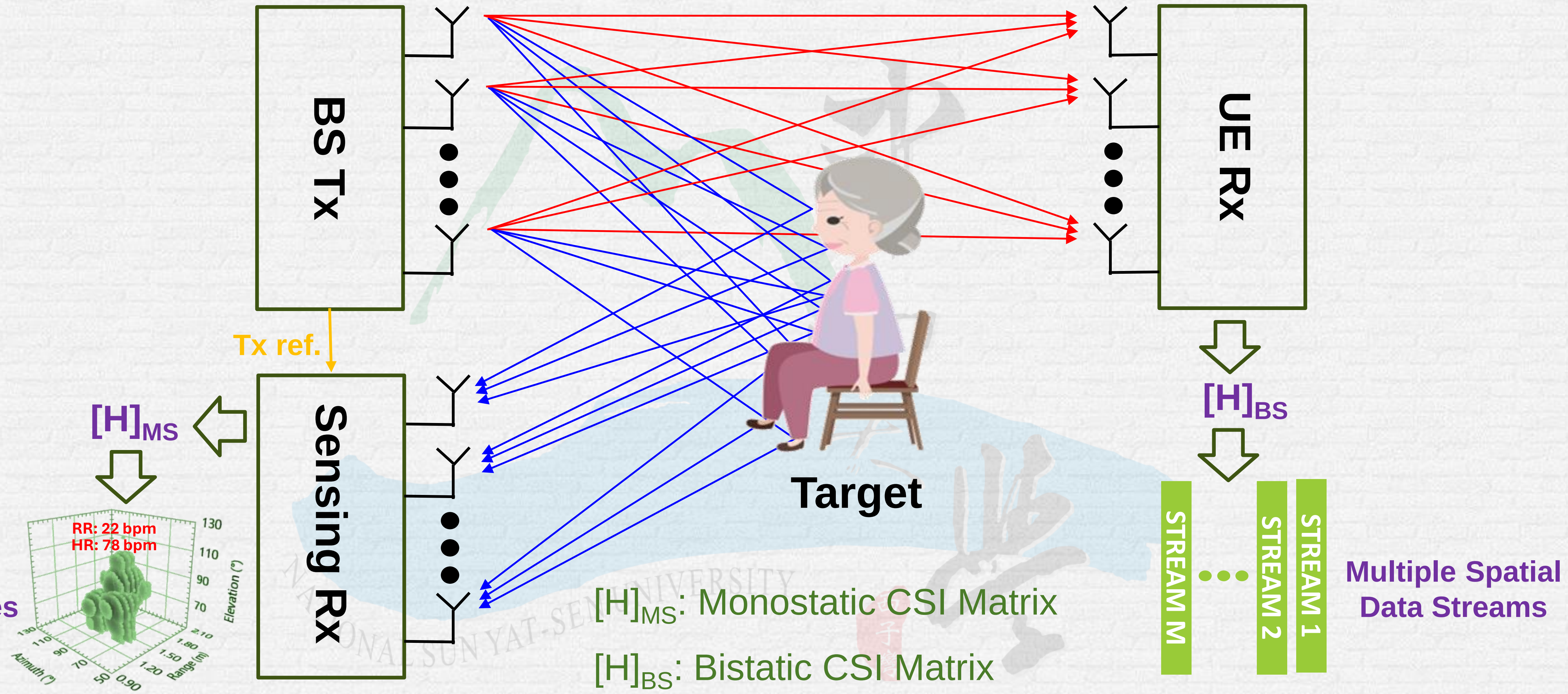


4D radar provides sensing information about targets' distances, azimuth angles, elevation angles, and Doppler shifts.

3D Imaging w/ μ-Doppler



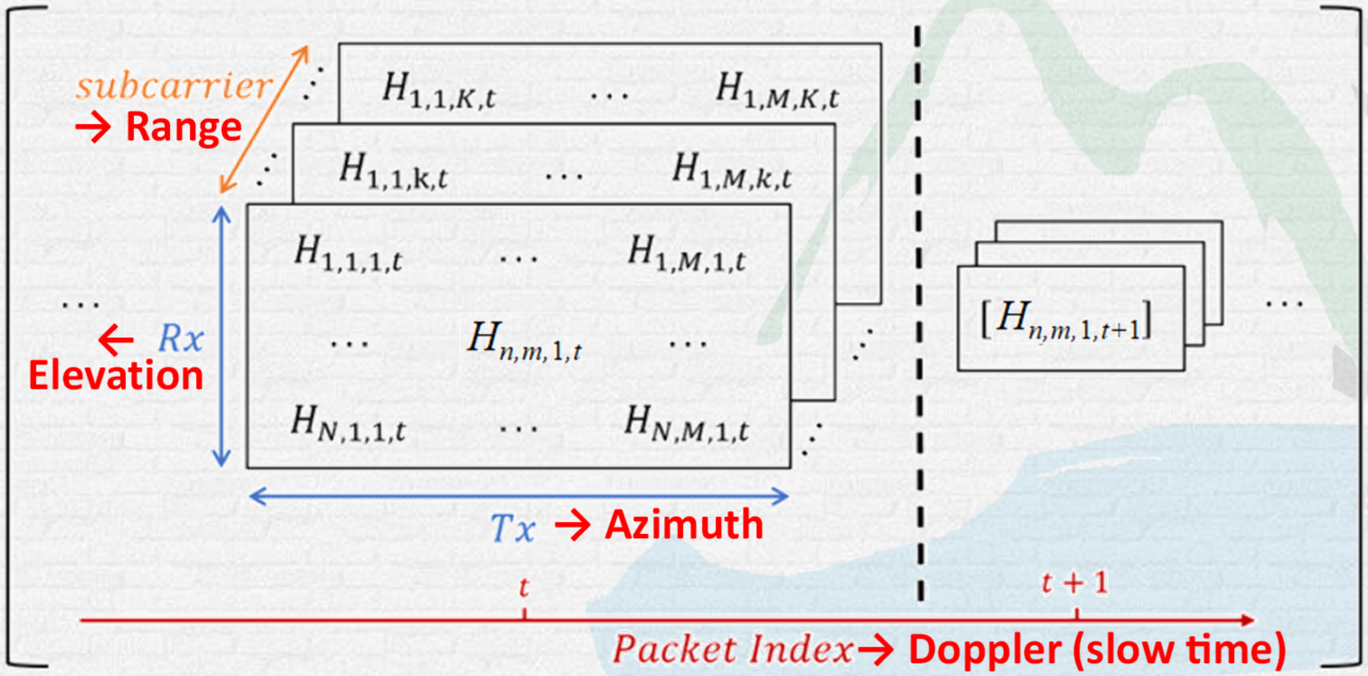
MIMO-ISAC System



$[H]_{MS}$: Monostatic CSI Matrix

$[H]_{BS}$: Bistatic CSI Matrix

4D Sensing via Monostatic CSI Matrix



$$H_{n,m,k,t} \Rightarrow I(\theta,\phi,R,t)$$

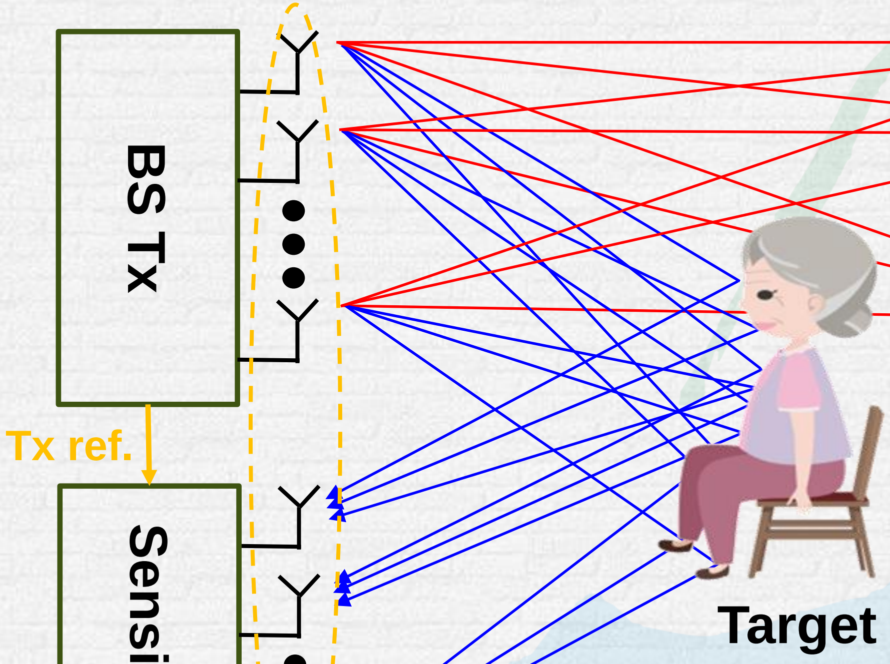
- **Sensing resolutions**
  - Range resolution: $\Delta R = c / (2 \cdot BW)$
  - Elevation resolution: $\Delta\theta = \lambda / L_{RxA}$
  - Azimuth resolution: $\Delta\varphi = \lambda / L_{TxA}$
  - Doppler velocity resolution: $\Delta v = \lambda / (2 \cdot CPT)$

where

c: speed of light; BW: bandwidth; λ: wavelength;
L_{RxA}: Rx array length; L_{TxA}: Tx array length;
CPI: coherent processing interval

4D Sensing from CSI: Tx/Rx antennas form an ***azimuth-elevation*** virtual array. Subcarrier responses yield ***range*** profiles, while packet index serves as the slow-time axis for ***Doppler*** analysis.

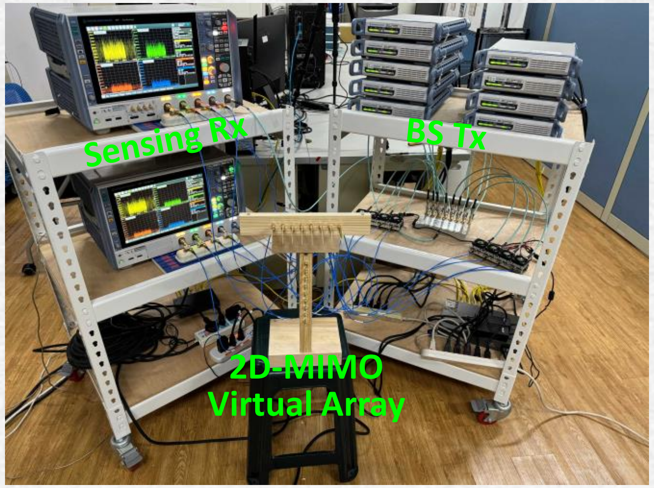
MIMO Passive Radar Leveraging Base Station CSI



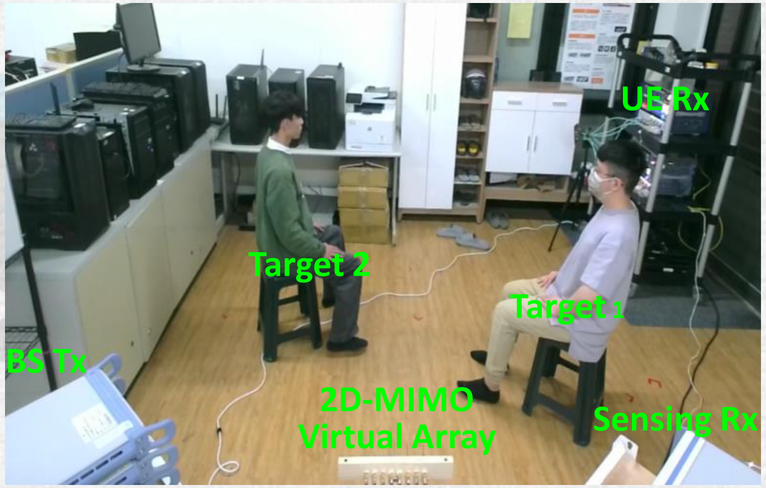
Video

B5G/6G Monostatic ISAC Scenario

Comm.	8T8R MIMO
Sensing	8T6R MIMO
Tx Freq.	FR3 7.1 GHz
Mod.	1644-subcarrier 64-QAM OFDM
BW	100 MHz
Tx Pwr.	-6 dBm

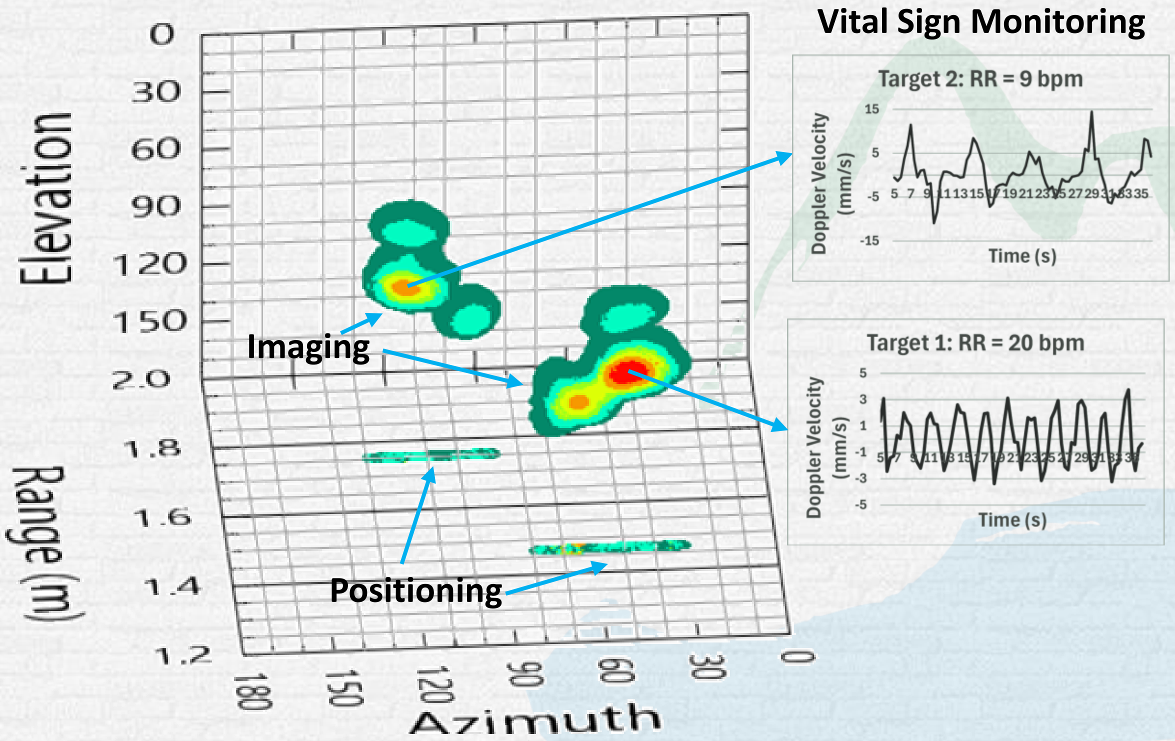


Prototype System

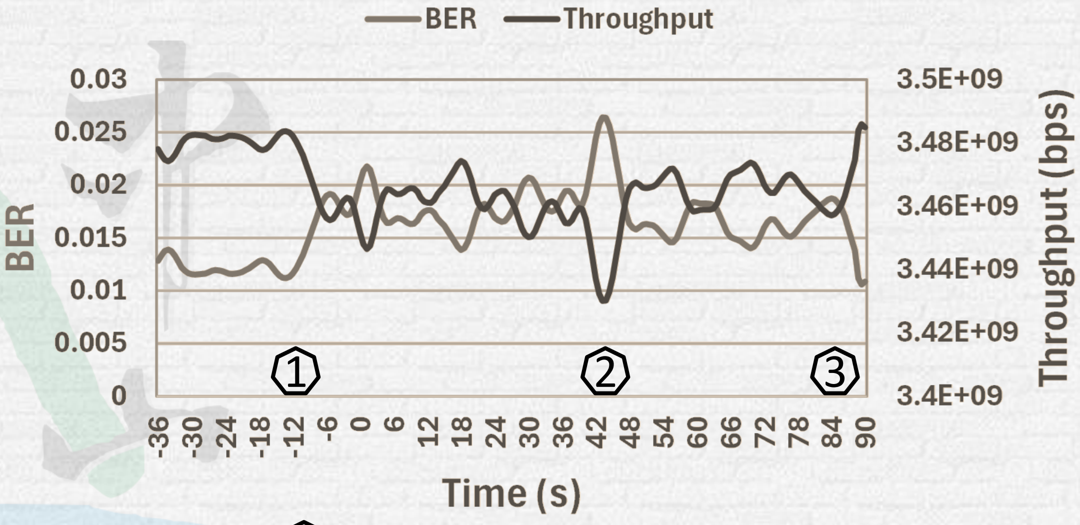


Sensing Scenario

Information Outputs in ISAC



Sensing Rx Output



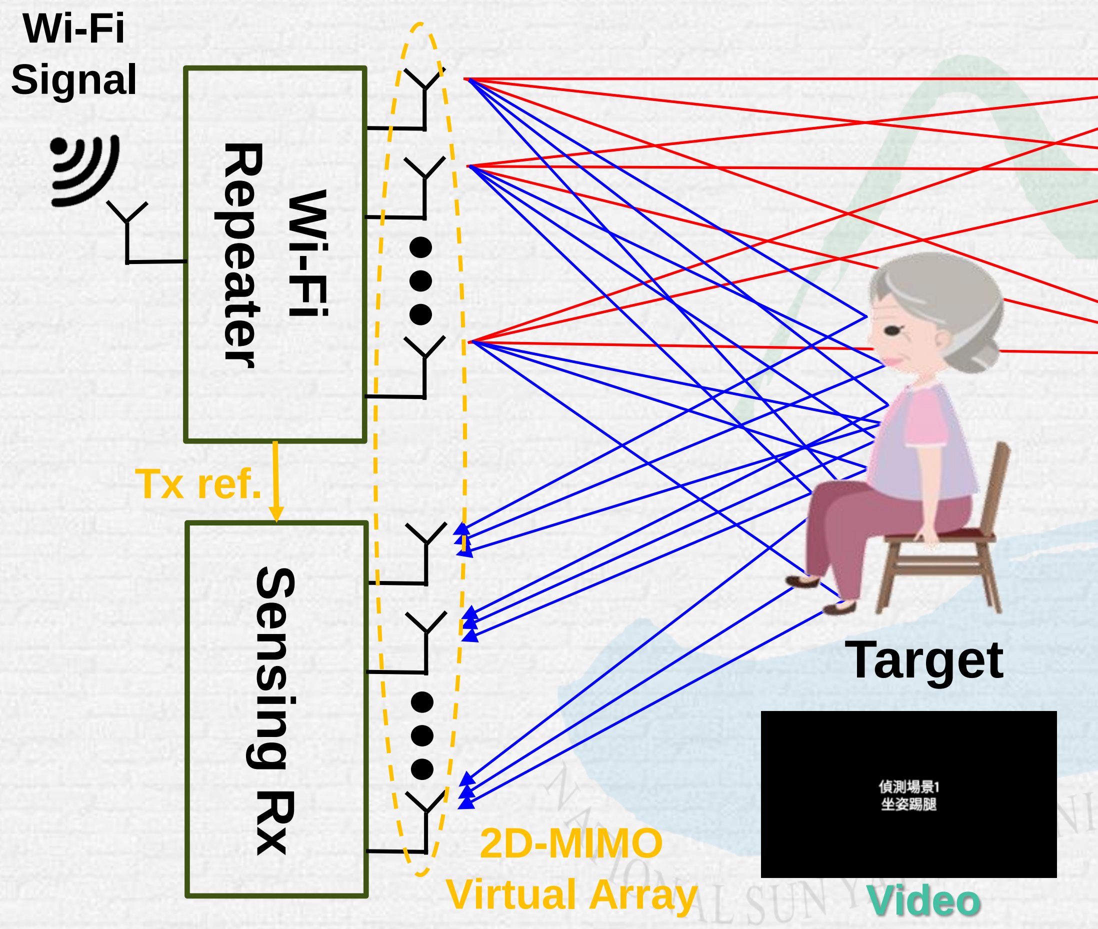
① Two subjects enter the field.

② Two subjects switch seats.

③ Two subjects exit the field.

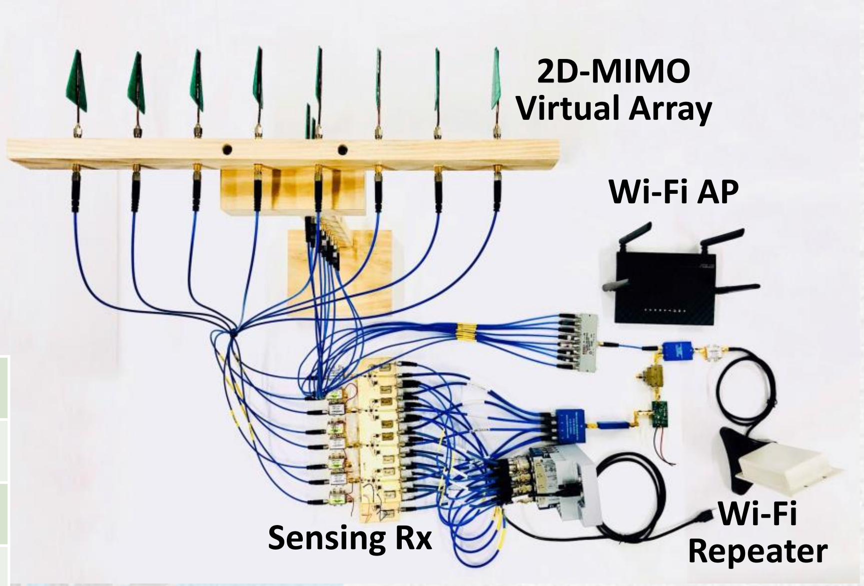
UE Rx Output

MIMO Passive Radar Utilizing Repeater Signals



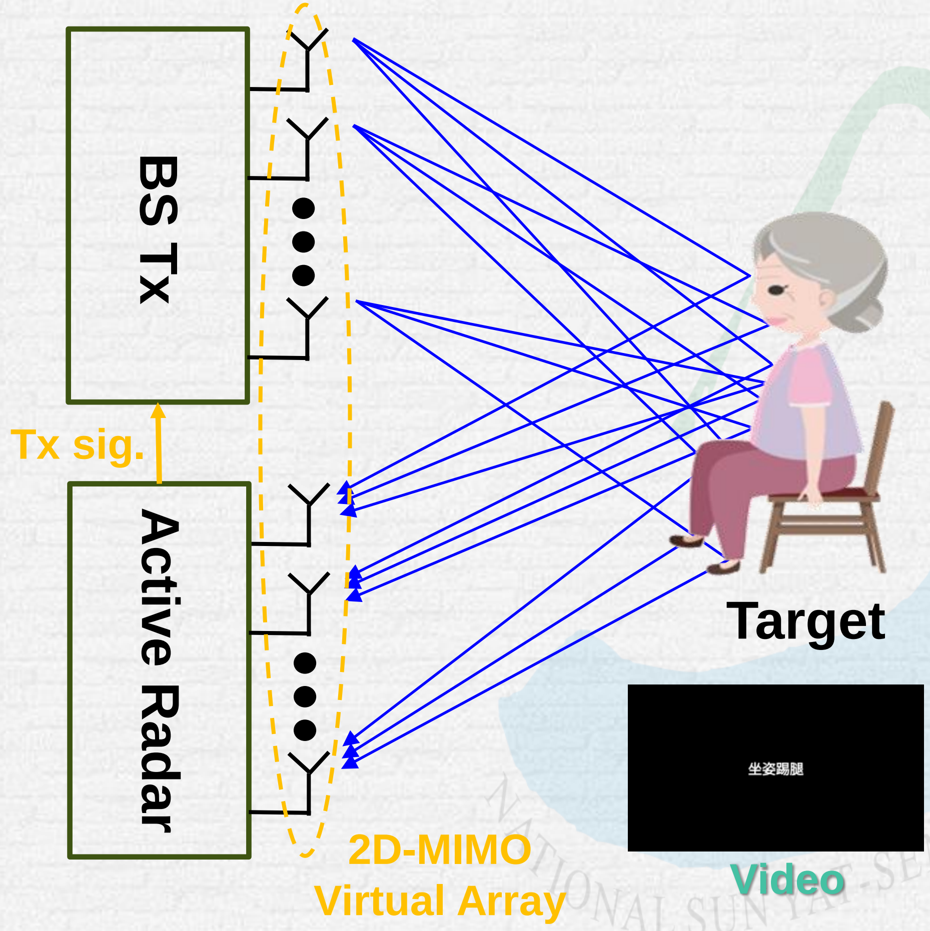
Comm.	4T4R MIMO
Sensing	8T8R MIMO
Tx Freq.	Wi-Fi 2.4 GHz
Mod.	64-subcarrier 64-QAM OFDM
BW	20 MHz
Tx Pwr.	5 dBm

Repeater-based Monostatic Sensing Scenario

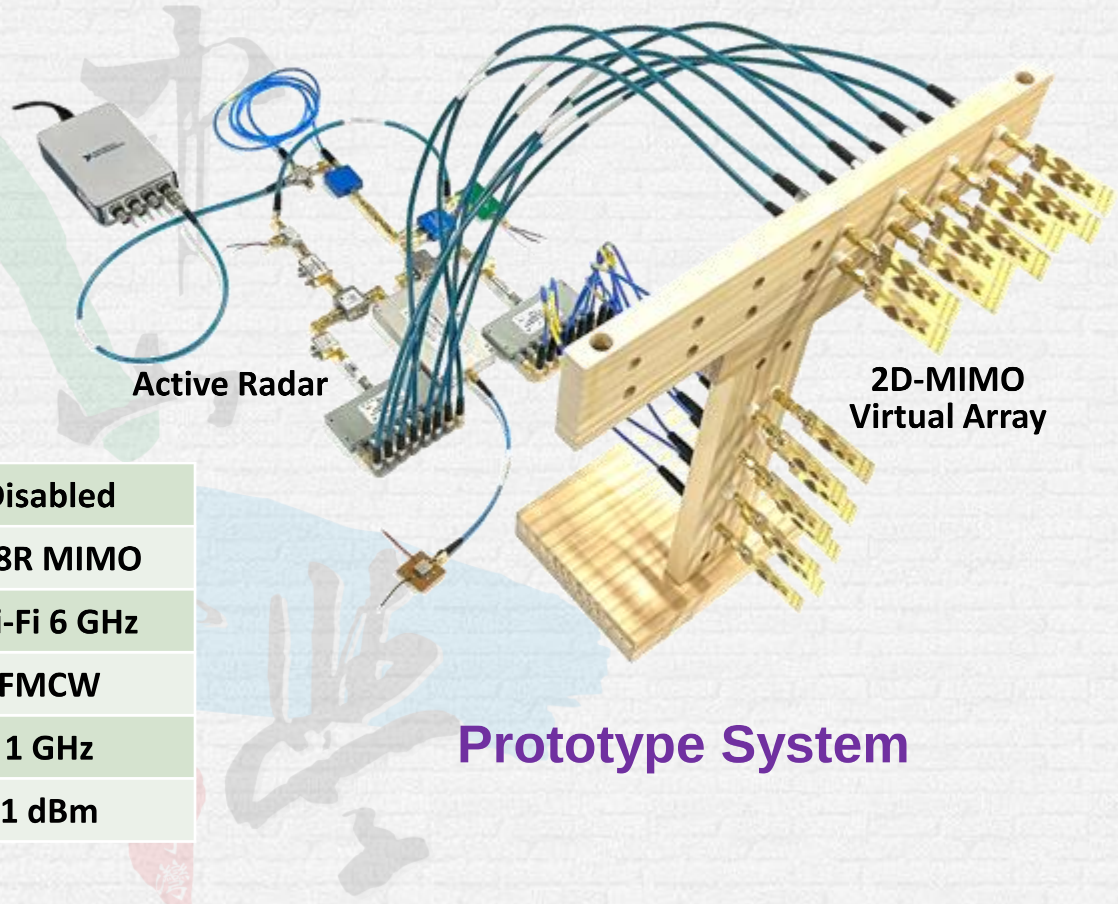


Prototype System

MIMO Active Radar Driven by Cognitive Sensing



Comm.	Disabled
Sensing	8T8R MIMO
Tx Freq.	Wi-Fi 6 GHz
Mod.	FMCW
BW	1 GHz
Tx Pwr.	1 dBm

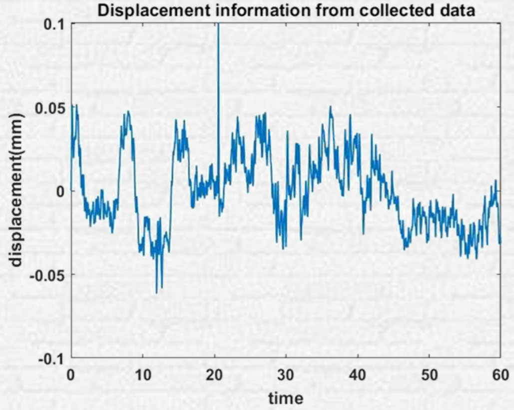


Prototype System

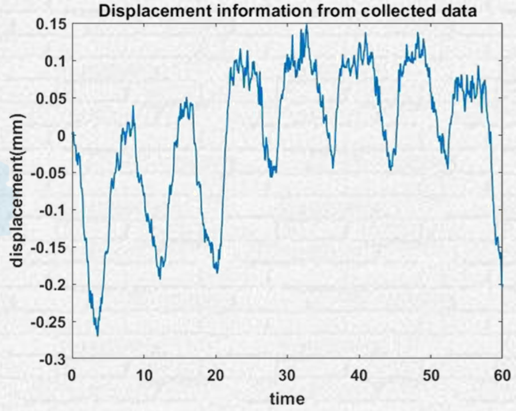
Cognitive Active Monostatic Sensing Scenario

RIS-Aided Sensing

RIS-Enabled Sensing in NLOS Regions

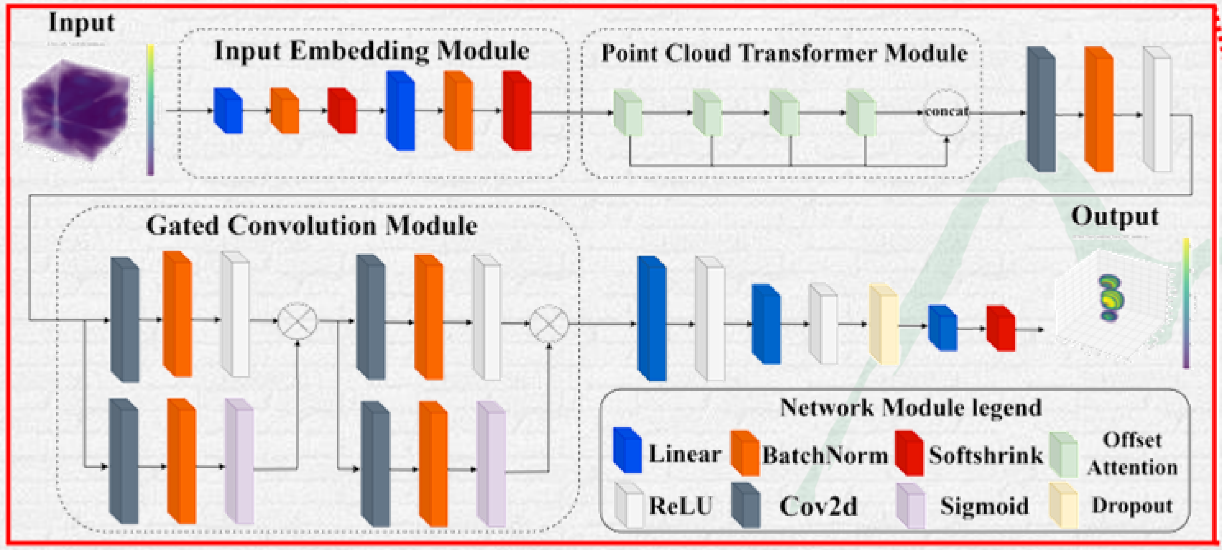


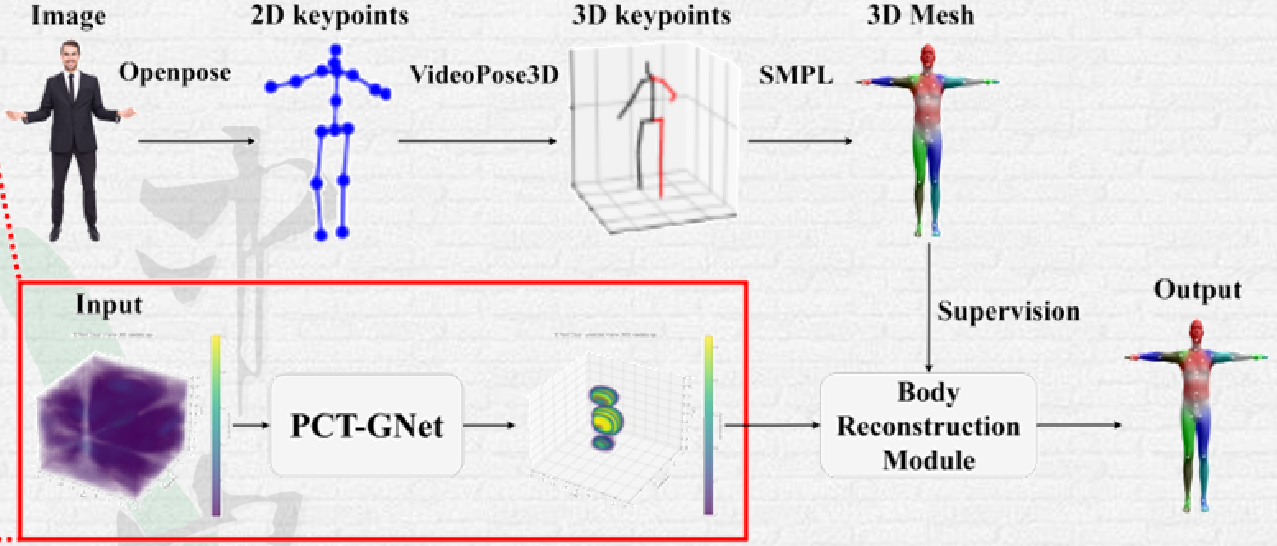
LC RIS Turned Off



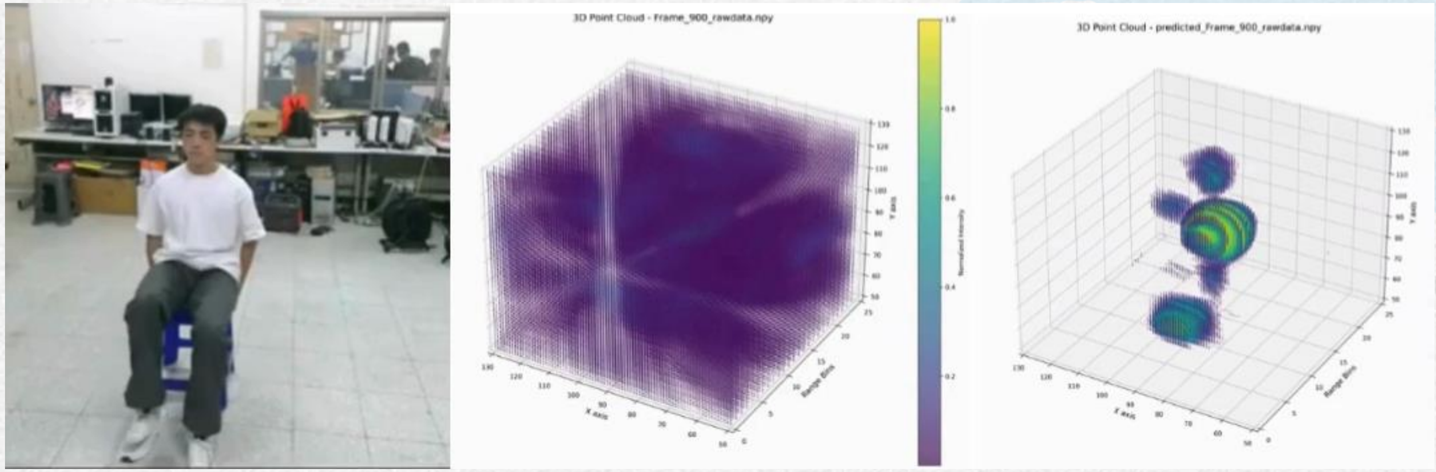
LC RIS Turned On

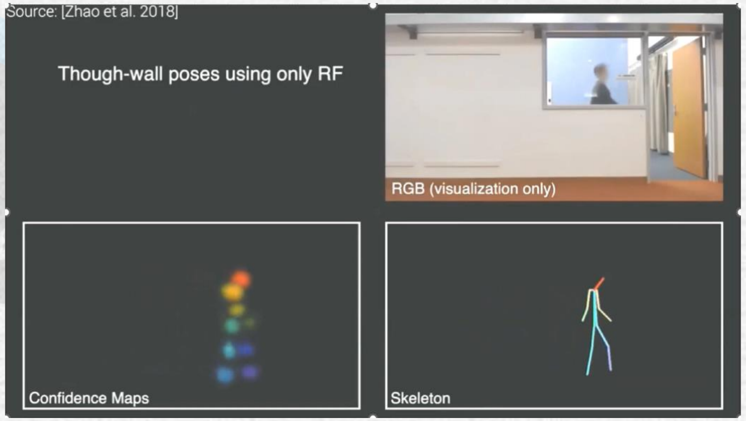
AI for Human Sensing





CSI-based AI Recognition Model implemented by Collaborator Prof. Chia-Hung Yeh





Video Source: MIT (2018)

Conclusions

- ISAC will make wireless sensing as widespread as wireless communication, greatly enhancing everyday convenience by ensuring continuous and ubiquitous access.
- Emerging MIMO-based 4D radar technology will seamlessly integrate with next-generation communication systems, establishing itself as the foundation of ISAC-enabled sensing.
- Human sensing will be a key application of ISAC, delivering comprehensive non-contact healthcare solutions.

NSTC Press Conference

Reserch Team

4D Radar Chip Demonstration


A9 生活新聞 2024年10月24日／星期四 自由時報

4D感測新技術 電磁波能測心跳

學界共同研發 未來老人跌倒、疲勞駕駛等都能隨時感知

癌細胞策反白血球 肺腺癌復發機轉

獨步全球 成大發現IL6醣化缺失 破解肺癌轉移路徑

Media Coverage

請於瀏覽器中搜尋「國科會4D感測」關鍵字查閱媒體報導內容