XG Mobile Promotion Forum

Beyond 5G White Paper
6G Radio Technology Project
“Sensing Technologies”

September 30, 2025

Wireless Sensing Working Group

Contents

Wireless Sensing WG

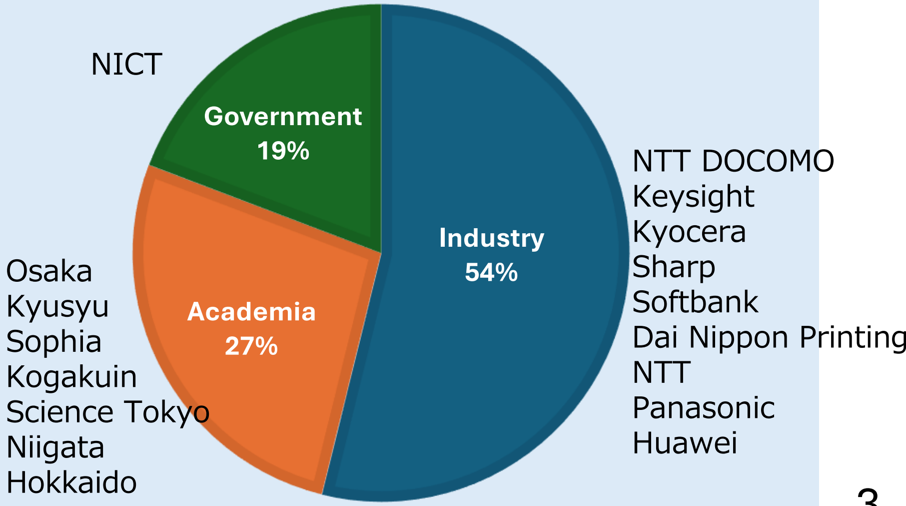
Objective

- ✓ Discuss use cases
- ✓ Identification of standardization trends
- ✓ Organize technical issues
- ✓ Promote Japan's uniqueness
- ✓ Promote PoC leading to practical application
- ✓ Share experimental data (database)
- ✓ Investigate applications

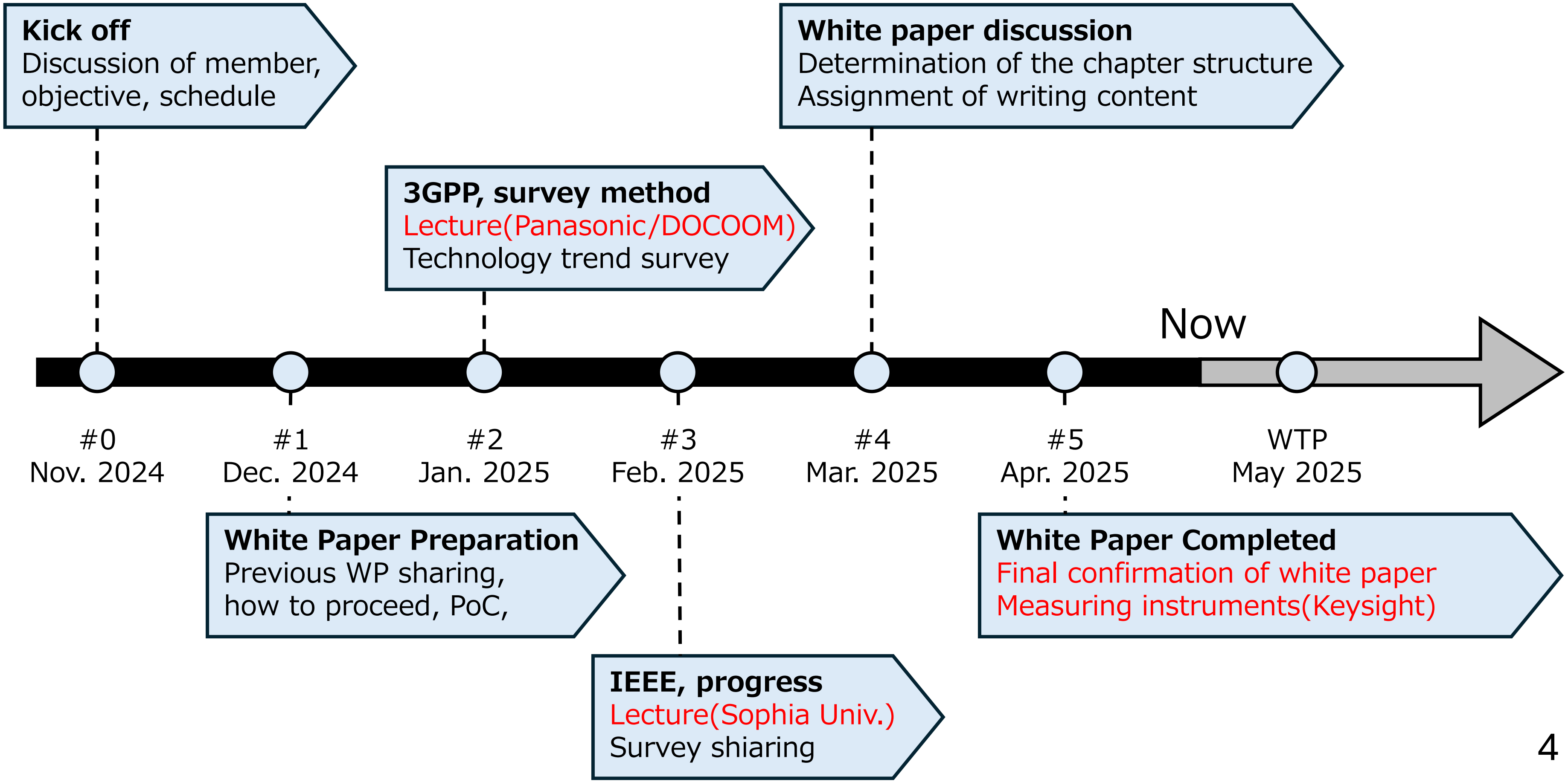
WG member

Chair: S. Suyama (NTT DOCOMO)
Vice Chair: T. Murakami (NTT)
H. So (Kogakuin Univ.)

Member: 28 (as of May 2025)



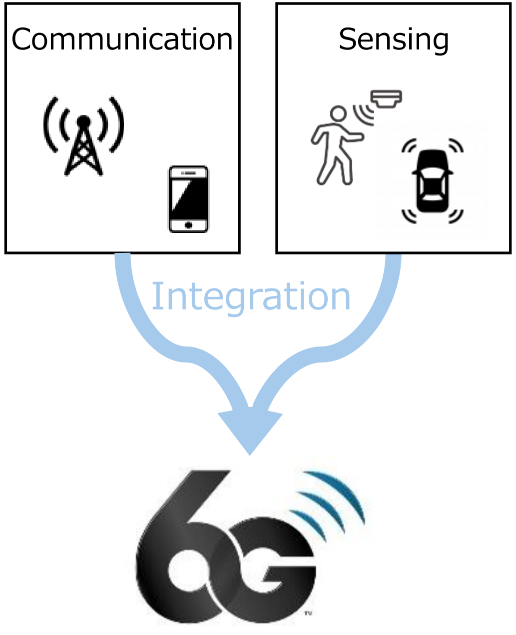
Discussions of Wireless Sensing WG



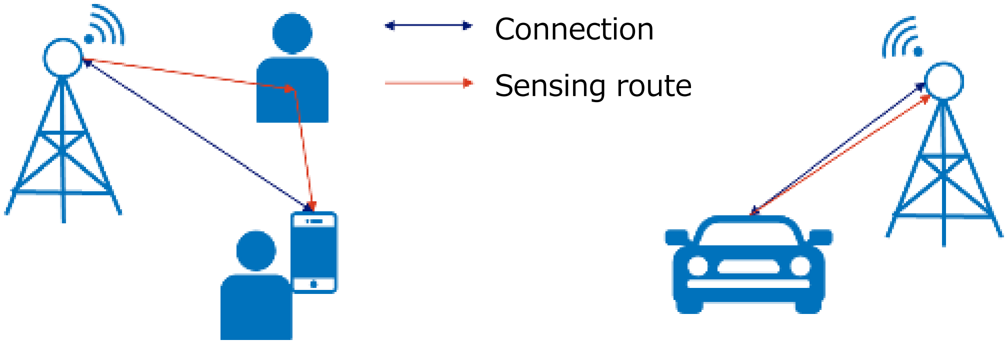
Contents

What is ISAC?

ISAC is a novel system that can provide advanced wireless connectivity and sensor information while reducing the cost/size/power consumption of base stations by integrating communication and sensing functions using radio waves.



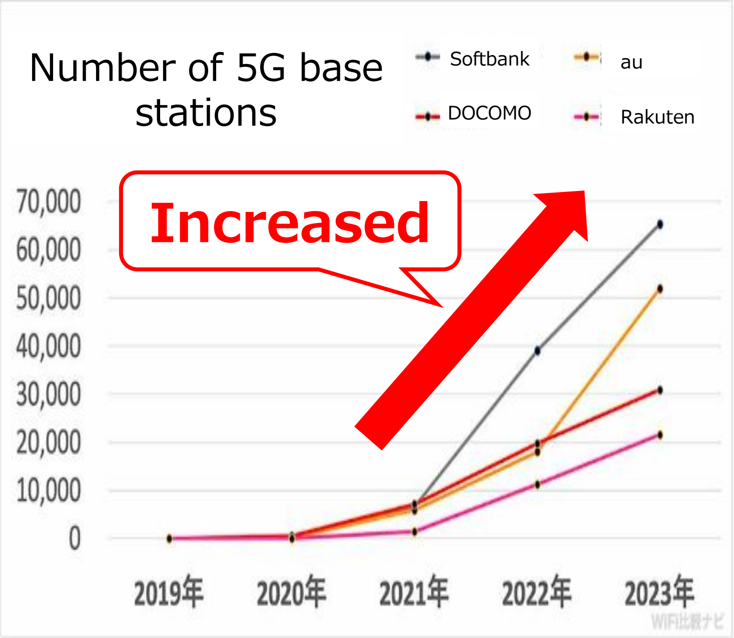
Low-cost Advancement Value-added



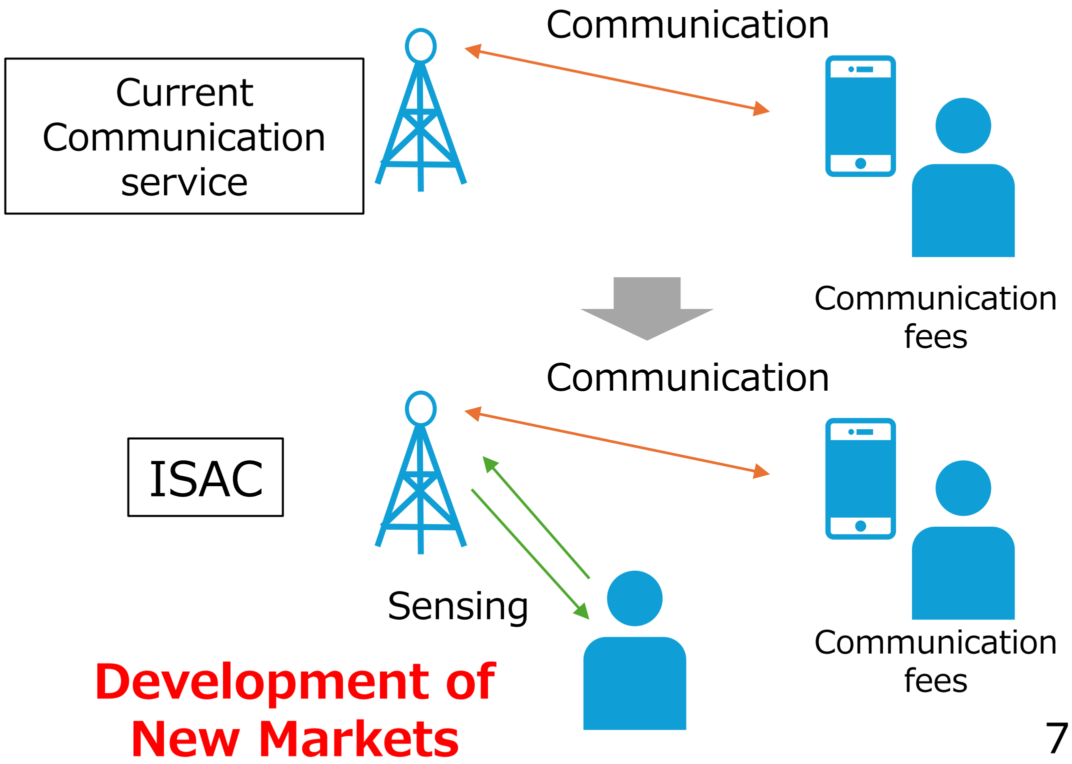
	Wireless	Infrared rays	カメラ
Area	~100m	~10m	～100m
Direction	Omni	Specific direction	Specific direction
NLOS	Good	Not good	Not good
Privacy	Good	Good	Not good

Target of ISAC

- The sensor range can be greatly expanded by using popular base stations as sensors.
- In addition to telecommunication services, the new market of sensing services can be developed.



Ref: https://hikaku-1234.com/basic/base-stations



Contents

Objectives of 3GPP Standardization [1]

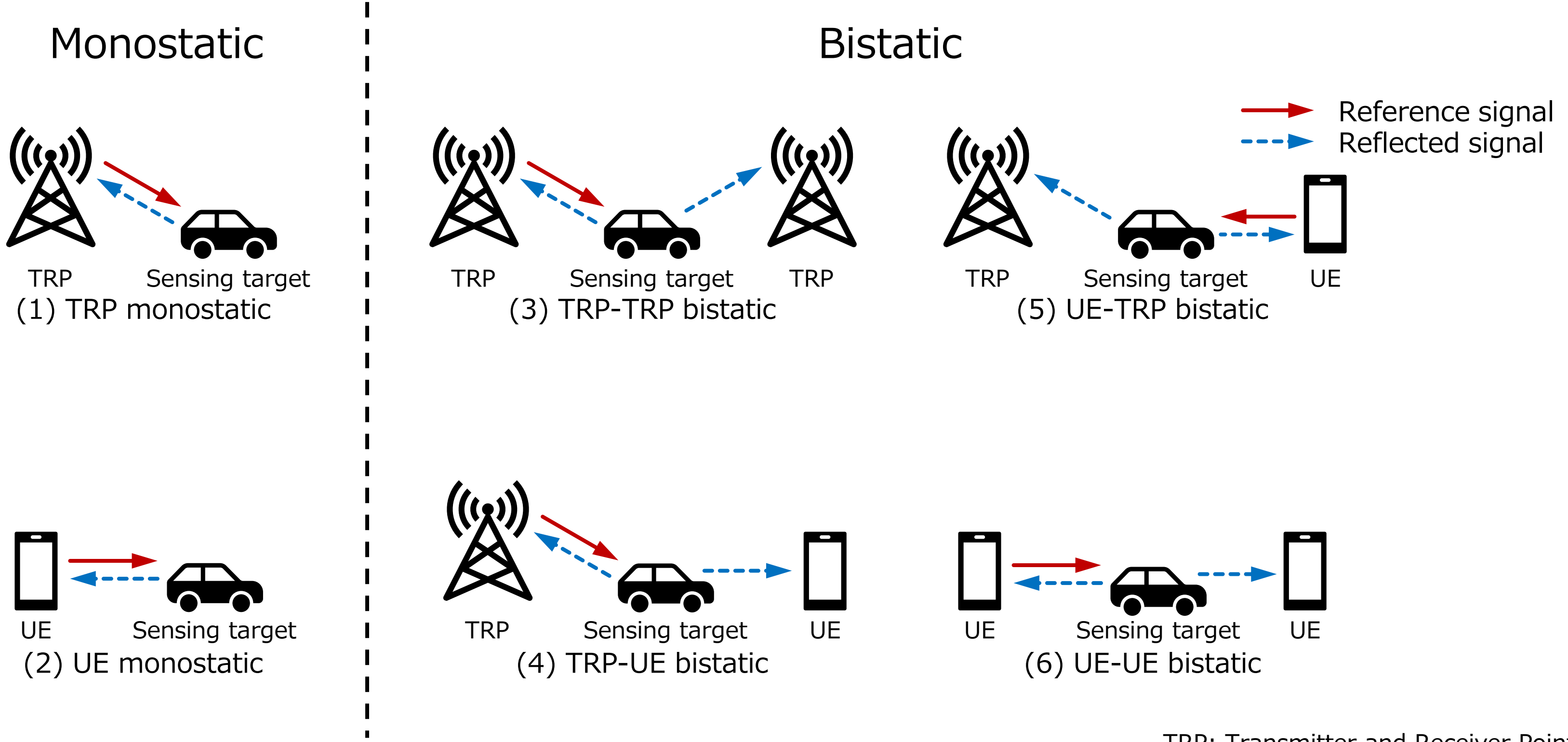
- Define channel modelling aspects to support object detection and/or tracking (as per the 3GPP Service and System Aspects 1 (SA1) meaning in the technical specification (TS) 22.137 [2])

- Construct a common modelling framework capable of detecting and/or tracking the following example objects (sensing targets) and to enable them to be distinguished from unintended objects:

1. Unmanned aerial vehicles (UAVs)
2. Humans indoors and outdoors
3. Automotive vehicles (at least outdoors)
4. Automated guided vehicles (AGVs e.g. in indoor factories)
5. Objects creating hazards on roads/railways

[1] 3GPP RP-242348, “Revised SID: Study on channel modelling for integrated sensing and communication (ISAC) for NR,” RAN#105, Melbourne, Australia, Sept. 2024.
[2] 3GPP TS 22.137 V19.1.0, “Service requirements for Integrated Sensing and Communication; Stage 1 (Release 19),” Mar. 2024.

Sensing Mode [1]



TRP: Transmitter and Receiver Point
UE: User Equipment

[1] 3GPP RP-242348, "Revised SID: Study on channel modelling for integrated sensing and communication (ISAC) for NR," RAN#105, Melbourne, Australia, Sept. 2024.

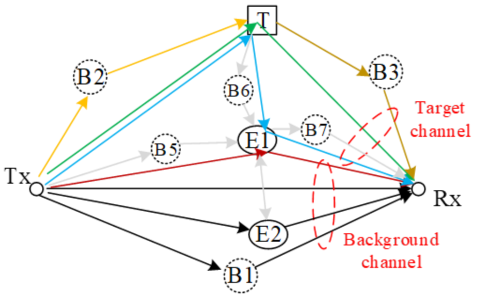
Channel Model

Discussions started at the March 2024 RAN1 meeting with a model based on sensing targets and background channels [3][4].
Detailed discussion of channels by targets, environmental objects other than targets, and background.
Stochastic cluster generation by targets, deterministic parameters of TRPs and targets basically using existing TR38.901 model [5].
Scattering points in the target are divided into single and multiple cases, and it is agreed that sensing in the single case is mainly based on the value of RCS[6][7].
Remaining issues such as polarization by target, diffraction and shielding models, and multiple scattering point models were discussed for agreement at the May 2025 meeting[8][9].

Channel model of ISAC[3]

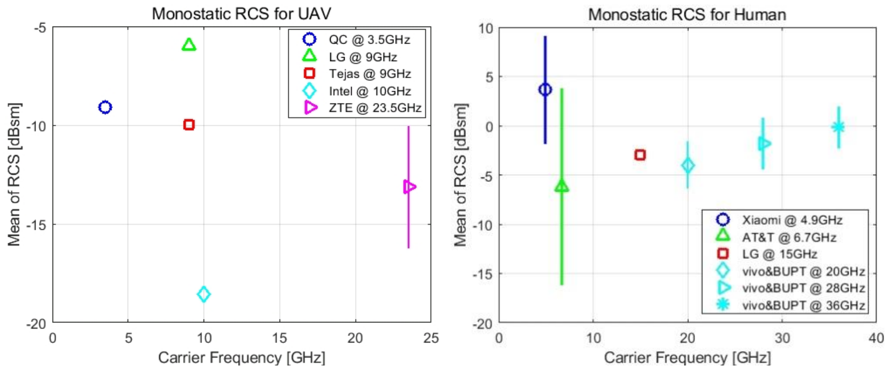
$$H_{ISAC} = H_{target} + H_{background}$$

- H_{target}: Propagation channel of target
- $H_{background}$: Propagation channel unaffected by target



T: Sensing target
E1, E2: Environment object (EO)
B1,⋯,B7: Stochastic clutter

Basic framework of ISAC channel model[3][4]



RCS values for Monostatic sensing by target [5]

[3] 3GPP R1-2401937, TSG RAN WG1 #116, Athens, Greece, March 2024.
[4] 3GPP R1-2403716, TSG RAN WG1 #116bis, Changsha, China, April 2024.
[5] 3GPP R1-2404636, TSG RAN WG1 #117, Fukuoka, Japan, May 2024.
[6] 3GPP R1-2409280, TSG RAN WG1 #118bis, Hefei, China, Oct. 2024.
[7] 3GPP R1-2410014, TSG RAN WG1 #119, Orlando, US, Nov. 2024.
[8] 3GPP R1-241041 (NTT DOCOMO, INC.), TSG RAN WG1 #119, Orlando, US, Nov. 2024.
[9] 3GPP R1-2501002, TSG RAN WG1 #120, Athens, Greece, Feb. 2025.

Sensing Target and Use cases [10]

1. UAVs

- UAV flight trajectory tracing
- Network assisted sensing to avoid UAV collision
- Sensing for UAV intrusion detection
- UAVs/vehicles/pedestrians detection near Smart Grid equipment

2. Humans indoors and outdoors

- Intruder detection in smart home
- Contactless sleep monitoring service
- Health monitoring at home
- Service continuity of unobtrusive health monitoring
- Roaming for sensing service of sports monitoring
- Immersive experience based on sensing
- Use case public safety search and rescue or apprehend

3. Automotive vehicles (at least outdoors)

- Sensing assisted automotive maneuvering and navigation
- Sensing for parking space determination
- Vehicles sensing for ADAS
- Sensing for automotive manoeuvring and navigation service when not served by RAN
- Blind spot detection

4. Automated guided vehicles (AGVs e.g. in indoor factories)

- AGV detection and tracking in factories
- Autonomous mobile robot (AMR) collision avoidance in smart factories

5. Objects crating hazards on roads/railways, within a minimum size dependent on frequency

- Pedestrian/animal intrusion detection on a highway
- Sensing for railway intrusion detection
- Sensing at crossroads with/without obstacle
- Accurate sensing for automotive manoeuvring and navigation service
- Integrated sensing and positioning in factory hall

(Combination of targets mentioned above and others)

- Rainfall monitoring
- Transparent sensing use case
- Sensing for flooding in smart cities
- Intruder detection in surroundings of smart home
- Sensing for tourist spot traffic management
- Protection of sensing information
- Sensor groups
- Seamless XR streaming
- Coarse gesture recognition for application navigation and immersive interaction

[10] 3GPP TR 22.837 V19.4.0, “Feasibility study on integrated sensing and communication (Release 19),” June 2024.

Ref: Sensing for UAV intrusion detection

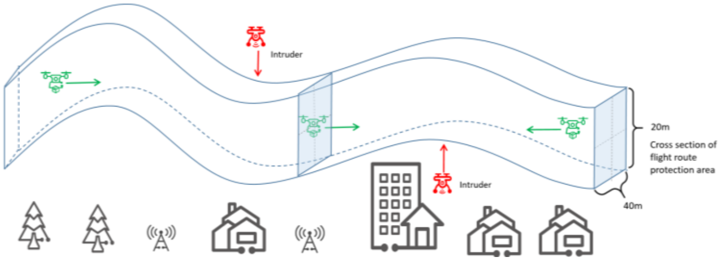
Description

- Low-altitude UAVs in smart cities have characteristics as large number, small size, wide flying zone, widely used to execute complex and diverse tasks.

⇒ Makes UAV supervision difficult if only using the traditional radar system

- Non-cooperative UAVs intruding some no-fly zone (e.g. airport, military base) would lead to serious consequences, e.g. exposing private information using the camera, blocking other UAV traffic on the flying route.

⇒ 5G System could be used for sensing the UAV intrusion in restricted area



UAV intrusion over flight routes [3]

Potential new requirements

1. The 5G system shall be able to provide a sensing service by using RAN to collect 3GPP sensing data.
2. The RAN shall be able to sense a target object by obtaining 3GPP sensing data without active involvement of the target object.
3. The 5G system shall provide mechanisms for an operator to transport 3GPP sensing data from RAN towards the core network.
4. The 5G system shall be able to provide a mechanism for a trusted third-party to request the sensing service, and the base station shall be able to operate sensing periodically or continuously in certain location area for a certain amount of time.
5. The 5G system shall be able to periodically expose sensing results to a trusted third-party application.
6. The 5G system shall provide a mechanism controllable by the operator, according to a business agreement, to report sensing result to a trusted third-party about a target object and multiple target objects when specific conditions are met.

Ref: Service continuity of unobtrusive health monitoring

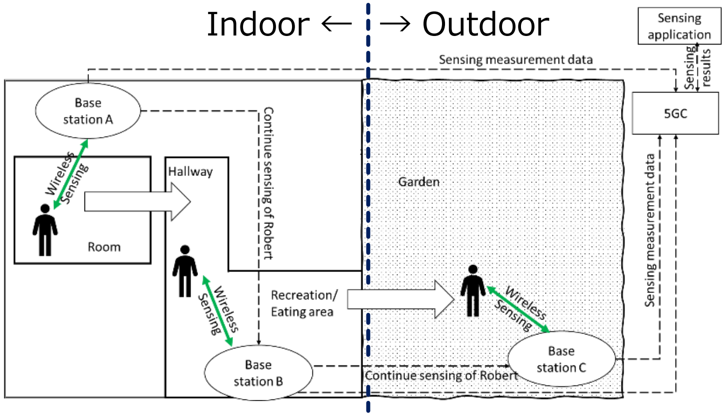
Description

- The deployed 5G system (installed in hospital or elderly home) includes multiple sensing devices.

⇒ Can perform health monitoring (one or more persons)

- ➢ Fall / activity detection of vital signs (e.g. heart rate or breathing rate)
- ➢ Wireless sensing of vital signs

- No need to recharge / replace the batteries of body worn sensors
- No need to remind / help people to wear them after they took them off (e.g. After take a shower).
- Installing cameras as an alternative has privacy concerns.



Service continuity between base stations A, B, and C [3]

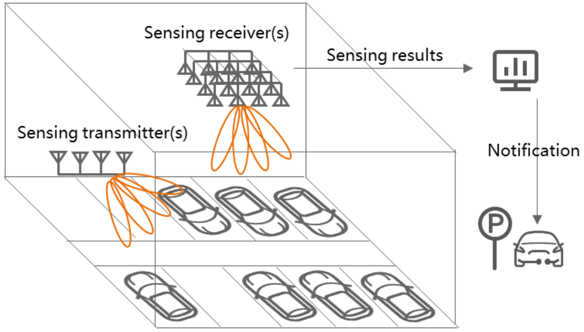
Potential new requirements

1. The 5G system shall support continuity of sensing of a target that may move across a sensing area that may be bigger than the coverage area of a single sensing transmitter.
2. The 5G system shall support simultaneous wireless sensing of a target by means of multiple sensing devices.
3. Subject to operator's policy, the 5G network may provide secure means for the operator to expose information on sensing service availability in a desired sensing service area location to a trusted third-party.

Ref: Sensing for parking space determination

Description

- Sensing technology can improve the user experience in parking garage via enabling the vehicle and parking garage to get more information.
- Connectivity is an important component in automatic parking e.g. [1]AVP and [2]AFP.
- 3GPP sensing technology can serve as the way to determine available parking spaces and the best route for a car to reach it.



Parking space determination (indoor deployment) [3]

Potential new requirements

1. The 5G system shall be able to provide sensing services in licensed and unlicensed spectrum.
2. The 5G system shall be able to authorize sensing receiver(s) and sensing transmitter(s) to participate in a sensing service.
3. Based on operator's policy, the 5G system shall enable a trusted third-party to request the activation of the sensing service with specific KPI requirement, as well as deactivation of the same service.
4. The 5G system shall be able to support charging for the sensing services.
5. The 5G system shall be able to provide a sensing service considering the interference to the sensing service caused by the sensing operations between multiple sensing transmitter(s) and sensing receiver(s).

[1]AVP: Automated Valet Parking [2]AFP: Automatic Factory Parking

Ref: AMR collision avoidance in smart factories

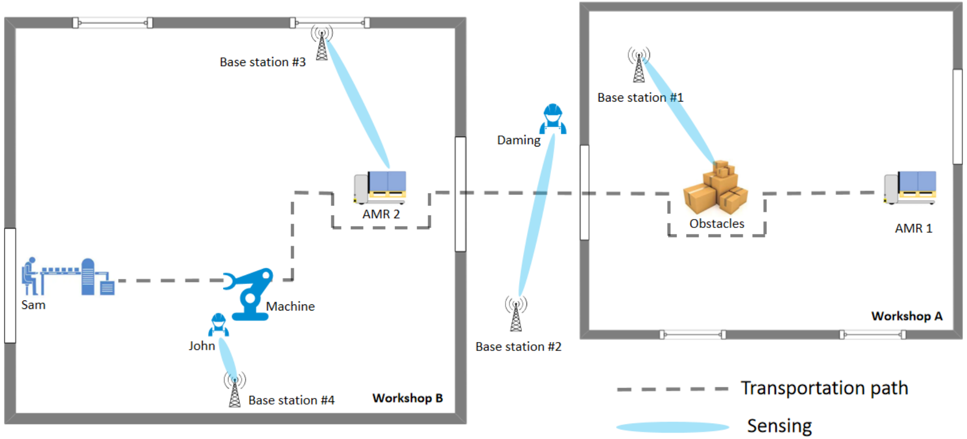
Description

- AMRs can travel automatically without derivatives or guides by the central unit (scheduling, routing, and dispatching decisions).

⇒ Currently being introduced in many logistics operations

e.g. manufacturing, warehousing, cross-docks, terminals, and hospitals

- During the AMR working process, the sensing range of a single AMR is limited and the surrounding environment status may be not detected in time.



Sensing people or obstacles detection in smart factory [3]

- 5G base stations deployed in a factory can not only provide communication capabilities for equipments in the factory but also sense the surrounding environment.

⇒ Sensing result can be utilized to improve efficiency and driving safety of AMRs.

Potential new requirements

- The 5G system shall be able to provide the continuity of sensing service for a specific target object, across indoor and outdoor.
- The 5G system shall be able to provide a secure mechanism to ensure sensing result data privacy within the sensing service area.

*AMR: Autonomous Mobile Robot

Ref: Sensing at crossroads with/without obstacle

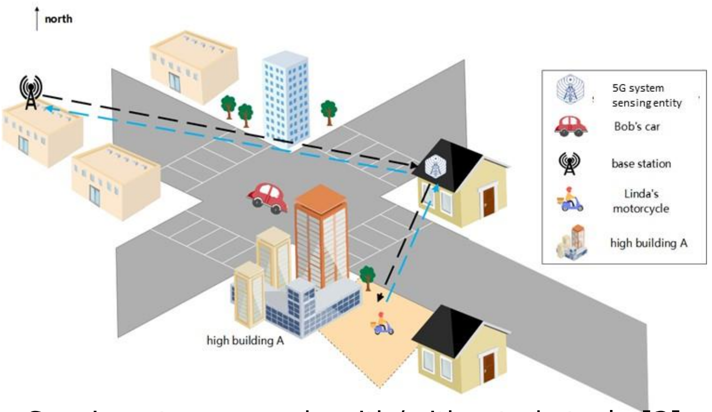
Description

- Traffic accidents often happen at the crossroads, for example owing to sudden appearance of the pedestrians from invisible place.

⇒ An urgent need to monitor the real-time road status for all days

- With the collaboration of trusted third-party (e.g. map service provider or ITS management platform), driving warning or assistant driving information can be provide timely to vehicles.
- The cameras and radars on *RSU always has some blind points.

⇒ 5G based sensing can provide sensing information to fill these gaps.



Sensing at crossroads with/without obstacle [3]

*RSU: Road-Side Unit

Potential new requirements

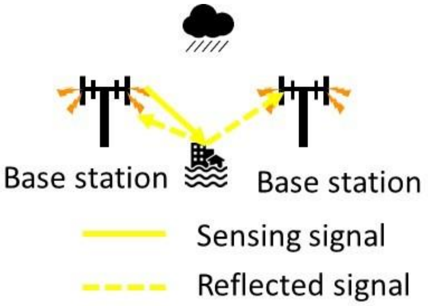
1. The 5G system shall be able to support a mechanism to provide available sensing service in a target sensing service area.
2. The 5G RAN shall be able to collect 3GPP sensing data from requested target sensing service area according to the operator's policy.
3. The 5G system shall be able to report the sensing result to the trusted third-party (e.g. the map service provider) with refresh rate, and controllable by the operator, according to a business agreement.
4. The 5G system shall support means for a trusted third-party application e.g. a map service provider to configure sensing per location.

Ref: Sensing for flooding in smart cities

Description

- Due to the recent climate change in recent years, it can be difficult to recognize places where flooding is expected to occur by using cameras and other sensors.

⇒ Using radio waves, it is possible to recognize places where flooding occurs in an efficient way.

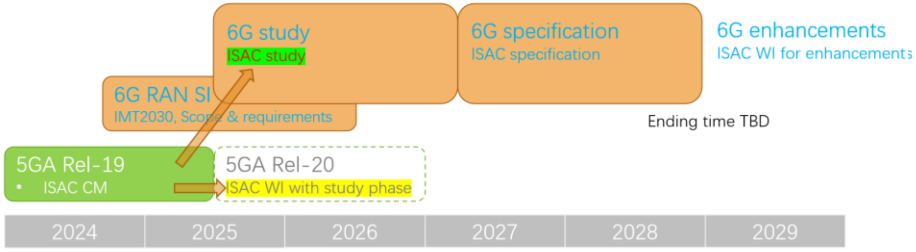


Sensing for flooding in smart cities [3]

Potential new requirements

1. Subject to operator policy, the 5G system shall be able to provide sensing result indicating disasters or other emergencies (e.g. flooding) in a given geographic area to authorized third parties <u>in a timely manner</u>.
2. Subject to regional or national regulatory requirements and operator policy, the 5G system shall be able to provide its public warning system with a warning notification based on sensing result indicating disasters or other emergencies in a given geographic area <u>in a timely manner</u>.
3. Subject to operator policy, it shall be possible for an authorized third party to configure the 5G system <u>to initiate sensing</u> for disasters or other emergencies in a given geographic area.

Progress of ISAC in 3GPP



An example of a roadmap for 3GPP ISAC standardization [11]

- Discussions will focus on the ISAC channel modelling for 5G-Advanced (5G-A) until the middle of 2025 [11], [12].
- The specifications for the commercial and industrial use of UAVs are prioritized owing to the rapid growth in the business and industrial demands [11]–[13].

Status of ISAC in 5G-A Release 19 [14]

TSG Tdoc of latest approved WI/SI description	RP-242348 [11]
Target completion date	Study item: June 2025
Overall completion level	70%: Normal progress
Rapporteur	Yingyang Li (Xiaomi) and Jerome Vogedes (AT&T)

Completed (Service Aspect 1)

- [Study Item] Feasibility study on ISAC [10]
- [Work Item] Service requirements for ISAC [11]

Ongoing [14]

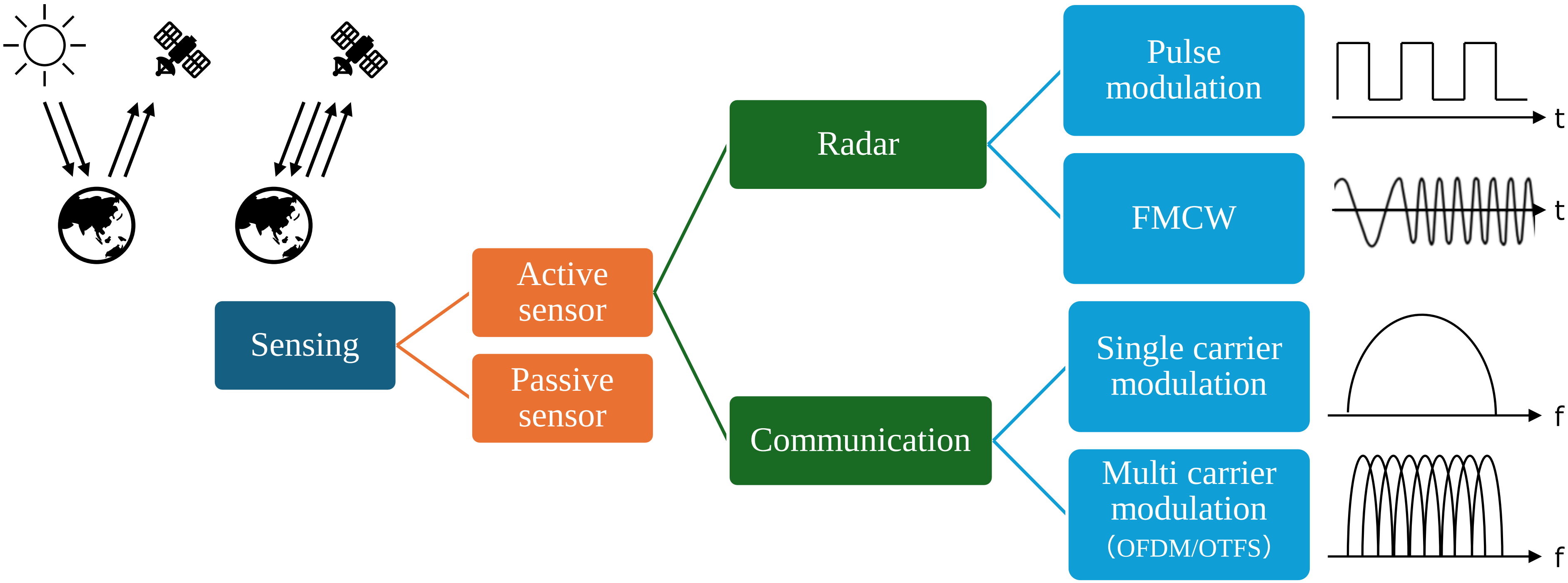
1. ISAC deployment scenarios
   - Calibration parameters, calibration results collection/analysis
2. ISAC channel modelling
   - Physical object model, polarization, power normalization, spatial consistency, angular correlation, blockage model, micro-Doppler, etc.

[11] 3GPP RP-242803 (Xiaomi), “Views on ISAC in 5GA Rel-20,” RAN #106, Madrid, Spain, Dec. 2024.
[12] 3GPP RP-242863 (China Telecom), “Motivation on integrated sensing and communication for 5G-A Rel-20,” RAN #106, Madrid, Spain, Dec. 2024.
[13] 3GPP RP-243151 (ZTE), “Support of ISAC in 5G-A Rel-20,” RAN #106, Madrid, Spain, Dec. 2024.
[14] 3GPP RP-250241, “Status report for SI: Study on channel modelling for Integrated Sensing And Communication (ISAC) for NR,” RAN #107, Incheon, South Korea, Mar. 2025.

Contents

Sensing Method Classification

- Sensing is classified into Passive type that senses naturally occurring electromagnetic fields and Active type that radiates radio waves
- Various modulation methods exist for radar and communication



Relationship between papers and use cases

- Various targets and use cases, both outdoor and indoor, are being considered
- Gradually moving from theoretical study to experimental verification phase

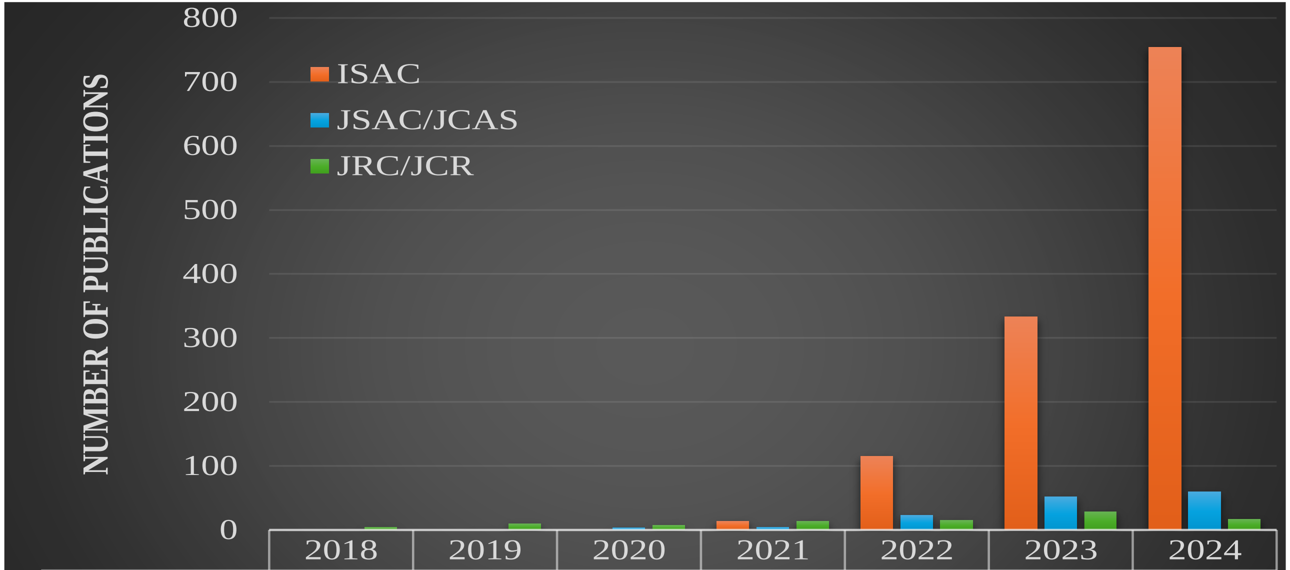
Use case		Publications
Outdoor	Human	[23][25][35][36][37][44][47][48][49][54][55][56][58][59][60]**[II-1][II-4][II-7][II-8][II-10]**
	Animal	
	Vehicle	[20][22][23][26][28][29][30][37][40][41][35][47][48][50][54][55][57]
	UAV	[23][24][32][38][39][43][48][61][62][63][64][65]
	Weather	[66][67][68][69][70][71][72][73][74][75]
Indoor		[21][27][31][33][34][42][46][50][51][52][53][76]**[II-2][II-3][II-9][II-10]**
Other		**[II-5][II-6]**

Articles containing experimental results

Articles to be included in the white paper

Trend of publications

- Since the definition of ISAC in IMT2030, the number of papers has rapidly increased
- Although JSAC/JCAS and JRC/JCR have a certain number of papers, ISAC is by far the most common.



	2018	2019	2020	2021	2022	2023	2024
ISAC				14	115	333	754
JSAC/JCAS	0	0	3	4	23	52	60
JRC/JCR	4	10	7	14	15	29	17

JSAC/JCAS: Joint Sensing And Communication/Joint Communication And Sensing
JRC/JCR: Joint Radar Communication/Joint Communication Radar

Related keywords

Keyword	Count			
ISAC	800		NOMA	77
sensors	361		deep learning	76
wireless communication	294		signal processing	75
radar	284		real-time systems	75
simulation	274		costs	74
array signal processing	266		bandwidth	68
OFDM	247		beamforming	66
6G	247		precoding	66
optimization	227		signal processing algorithms	66
signal to noise ratio	211		radar tracking	64
receivers	189		antenna arrays	63
interference	185		millimeter wave communication	63
autonomous aerial vehicles	180		channel models	63
estimation	167		quality of service	61
channel estimation	156		training	61
reconfigurable intelligent surfaces	155		transmitting antennas	59
transmitters	142		imaging	58
wireless sensor networks	137		parameter estimation	56
location awareness	131		radio frequency	55
time-frequency analysis	130		throughput	55
conferences	124		performance evaluation	54
symbols	116		heuristic algorithms	54
resource management	113		approximation algorithms	54
base stations	110		delays	52
object detection	102		waveform design	51
spectral efficiency	101		protocols	50
hardware	101		system performance	47
downlink	99		robot sensing systems	47
radar antennas	96		MIMO	46
interference cancellation	92		radar signal processing	46
uplink	89		antenna measurements	44
vehicular and wireless technologies	87		full-duplex system	44
wireless networks	85		physical layer security	43
radar detection	84		target tracking	43
modulation	82		internet of things	43
receiving antennas	79		uav	43
measurement	77			

Use case

Technical

Other

Contents

Research and development case studies in Japan

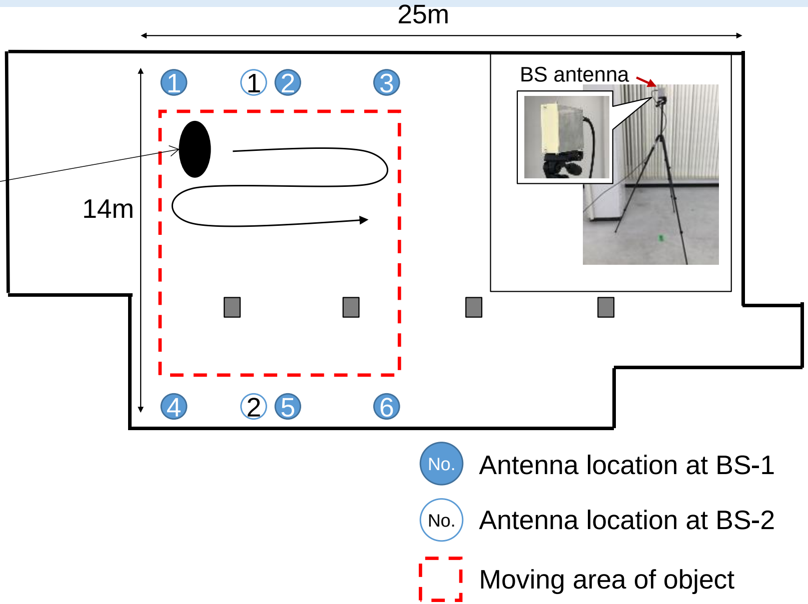
Section No.	Title / Authors
II-1	**CSI-Based Device-Free Sensing Using Deep Learning with 5G NR 28 GHz Band** Tomoki Murakami, Shinya Otsuki, NTT Corporation Yutaka Musaka, Yoshifumi Morihiro, Huiling Jiang, Satoshi Suyama, NTT DOCOMO, INC. Yasushi Maruta, NEC corporation
II-2	**Indoor Experimental Evaluation of Device-free Localization Schemes Using Channel State Information in Distributed Antenna Systems** Osamu Muta, Kyushu University Tomoki Murakami, Shinya Otsuki, NTT Corporation
II-3	**CSI2Image: CSI-to-Image Conversion using a Generative Model** Sorachi Kato, Takuya Fujihashi, Takashi Watanabe, Shunsuke Saruwatari, Osaka University Tomoki Murakami, NTT Corporation
II-4	**Use Cases for CSI Sensing with an Example of Pedestrian Movement Direction Identification** Masakatsu Ogawa, Sophia University
II-5	**Integrated Sensing and Communication (ISAC)** Chen Yan, Huawei Technologies Koshimizu Takashi, Huawei Technologies Japan
II-6	**Space-Time Synchronization** Tetsuya Ido, Nobuyasu Shiga, Motoaki Hara, Yuichiro Yano, Satoshi Yasuda, Ryuichi Ichikawa, NICT
II-7	**Experimental Evaluation of WLAN-based Device-Free Localization Using CSI in Outdoor and Large-scale Indoor Environments** Osamu Muta, Shunsuke Shimizu, Kyushu University Tomoki Murakami, Shinya Otsuki, Hanae Otani, NTT Corporation
II-8	**A Fundamental Study on the Relationship Between Pedestrian Traffic and Wi-Fi CSI with Existing Outdoor Access Points** Masakatsu Ogawa, Sophia University
II-9	**Multipath-RTI: Millimeter-Wave Radio Based Device-Free Localization** Minseok Kim, Niigata University
II-10	**Verification in an anechoic chamber toward the realization of a radio wave camera using a mobile communication system** Kazuma Tomimoto, Tomonori Ikeda, Ryo Yamaguchi, Toshiki Hozen, Syumpei Tabuchi, SoftBank Corp. Research Institute of Advanced Technology

II-1

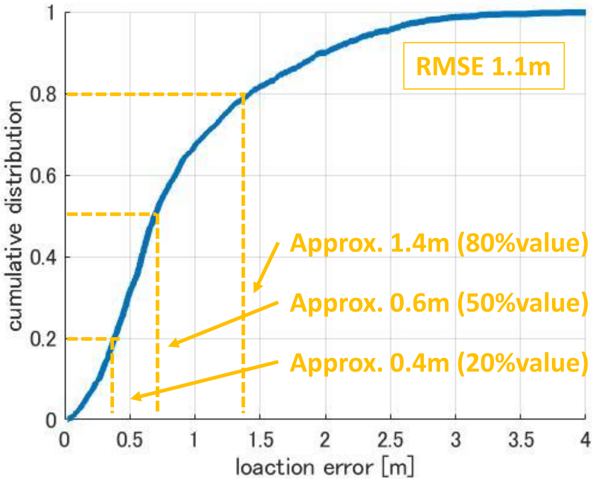
CSI-Based Device-Free Sensing Using Deep Learning with 5G NR 28 GHz Band

NTT Corporation, NTT DOCOMO, INC., NEC corporation

Integrated Sensing and Communication (ISAC) is gaining attraction as it aims to bring added value to next-generation mobile communication networks. This paper offers an overview of the device-free sensing technology, which detects target object without the need for mobile terminals, utilizing deep learning. It further introduces the effectiveness of this technology based on our experiments conducted on a radio testbed equipped with the physical layer specifications of the 5G (NR) 28 GHz band.



Experimental environment

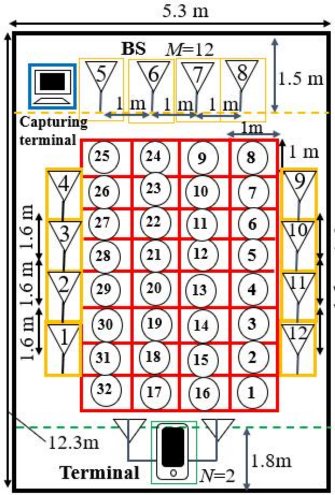


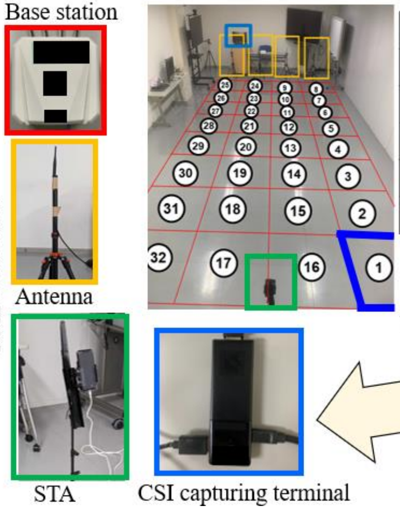
Experimental results

II-2 Indoor Experimental Evaluation of Device-free Localization Schemes Using Channel State Information in Distributed Antenna Systems

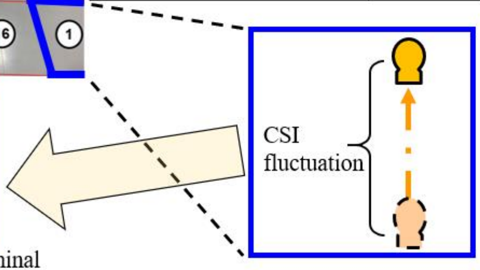
Kyushu University, NTT Corporation

Wireless communication system-based localization techniques that use channel state information (CSI) have attracted much attention. Performance of the CSI-based localization schemes depends strongly on the selected feature information and antenna placement. Herein, we present a real-time CSI-based device-free localization scheme for distributed antenna systems, where CSI feedback frames are collected and used as a dataset for machine learning (ML)-based localization. Experimental results confirmed that the developed localization scheme is effective for detecting a target in an indoor environment. We also discuss how much performance improvement can be expected when antenna placement is given properly.

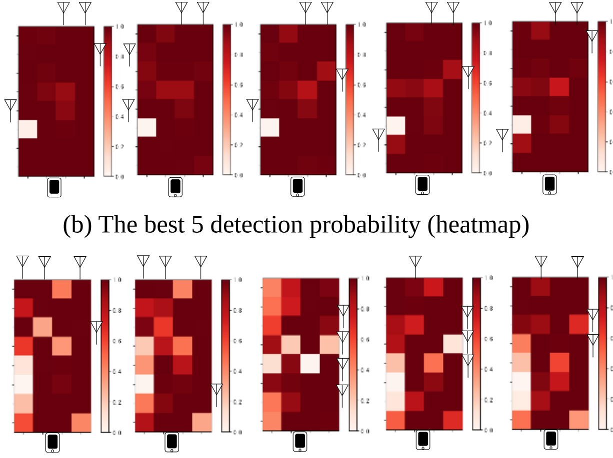




Number of antennas at AP	M=4
Number of antennas at STA	N=2
Antenna height	1m
Bandwidth	20MHz
Carrier frequency	5.18GHz
Number of subcarriers	52



Experiment scenario and setup



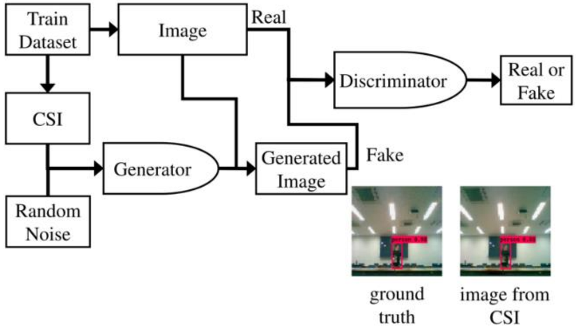
(b) The best 5 detection probability (heatmap)

(c) The worst 5 detection probability (heatmap)

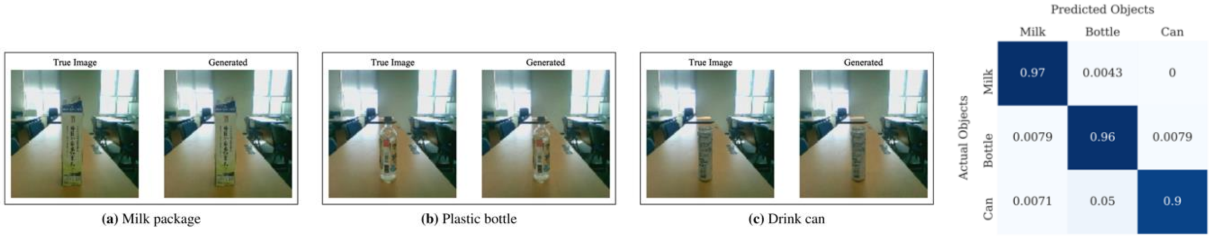
CSI2Image: CSI-to-Image Conversion using a Generative Model

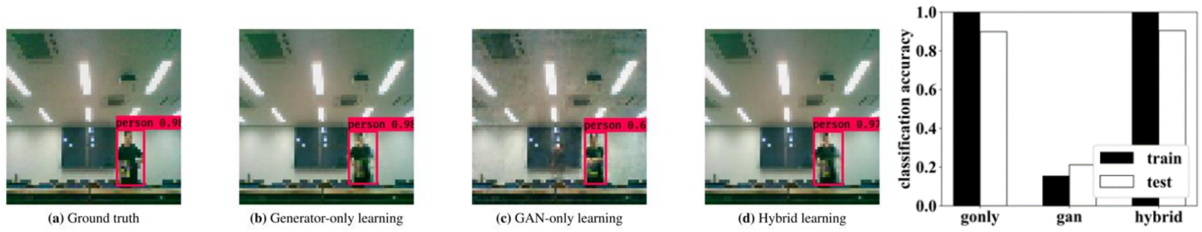
Osaka University, NTT Corporation

Wireless sensing studies based on channel state information (CSI) continue to be successful in various sensing tasks. However, we still have no clear answer to what extent we can extract the environmental parameters of physical space from CSI. We proposed CSI2Image to address such a challenging issue. It converts CSI observations into RGB images corresponding to the physical space using generative adversarial network (GAN) architecture. The generated RGB images intuitively show the relationship between the CSI observations and the physical space and potentially help us to extract many environmental parameters for multi-purpose sensing system.



Overview of CSI2Image





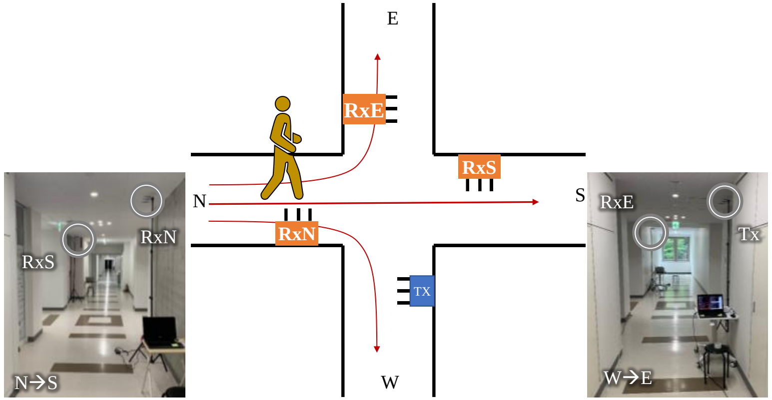
Qualitative and quantitative evaluation for different sensing tasks

II-4

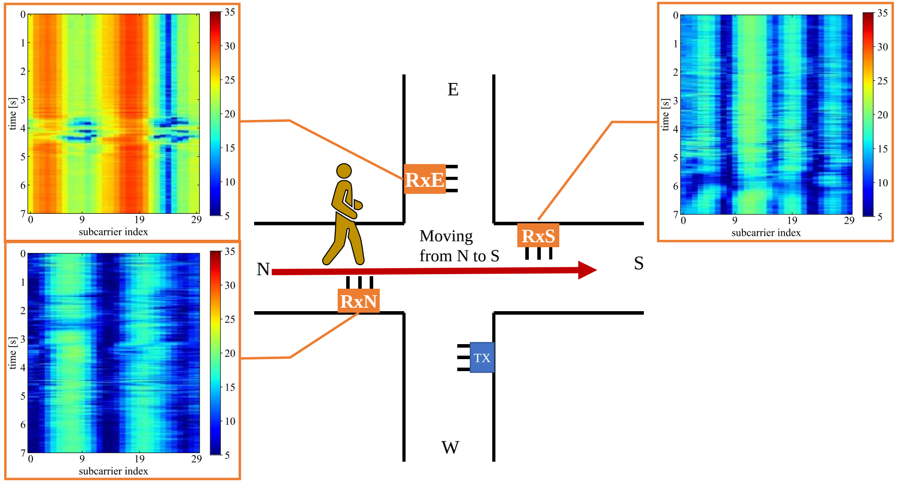
Use Cases for CSI Sensing with an Example of Pedestrian Movement Direction Identification

Sophia University

The original purpose of communication is to convey information. Channel state information (CSI) is used for high-speed transmission and can also function as a sensor. Adding sensing ability to the communication function is expected to open up new services and applications. This paper describes use cases for CSI sensing from the perspectives of commercial products and my research, specifically pedestrian movement direction identification.



Experimental environment



CSI at each receiver

II-5

Integrated Sensing and Communication (ISAC)

Huawei Technologies, Huawei Technologies Japan

6G will serve as a distributed neural network for the future Intelligence of Everything. Network Sensing and Native AI will become two new usage scenarios in the era of connected intelligence. 6G will integrate sensing with communication in a single system. Radio waves can be exploited to "see" the physical world and make a digital twin in the cyber world. This paper introduces the concept of integrated sensing and communication (ISAC) and typical use cases, and provides two case studies of how to use 6G ISAC to improve localization accuracy and perform millimeter level imaging using future portable devices. The research challenges to implementing ISAC in practice are discussed.

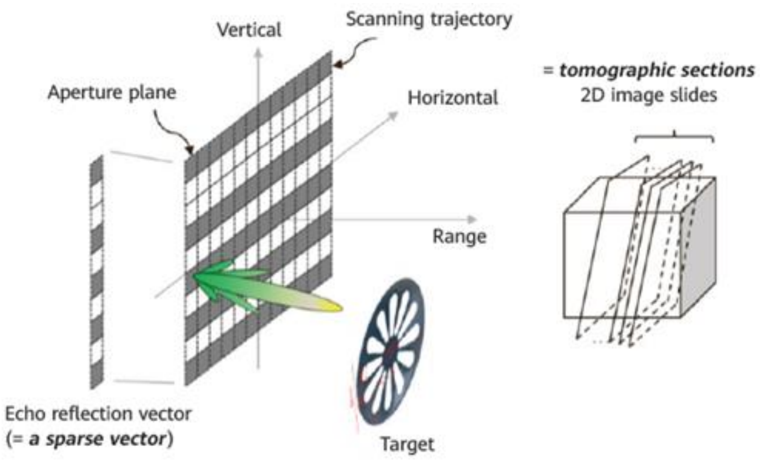
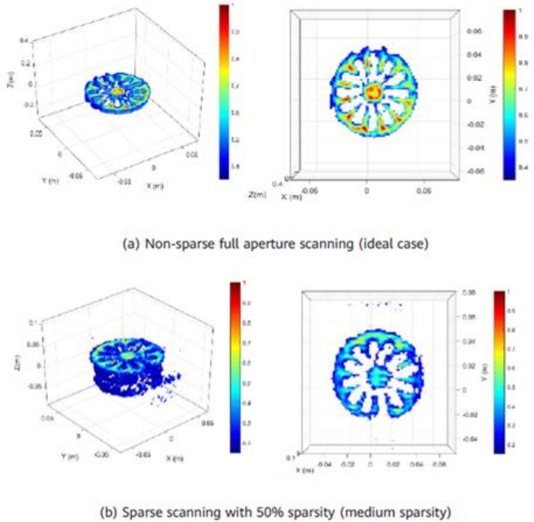


Illustration of the sparse scanning approach and the tomographic imaging techniques

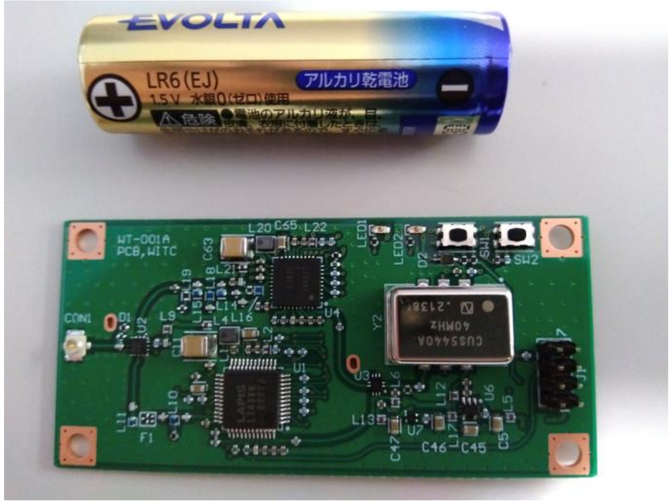


Imaging results at different sparsity configurations

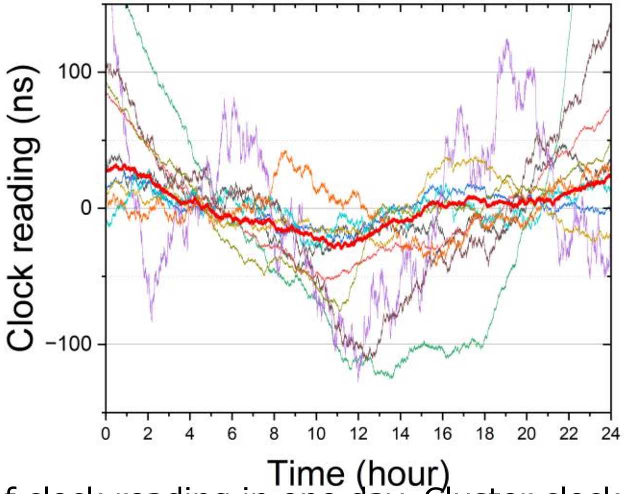
Space-Time Synchronization

NICT

For mobile communication technology to transform from a means of man-to-man communication to an infrastructure for various vertical sectors in society, the method of the time synchronization should shift from the traditional leader-follower structure to autonomous distributed synchronization. Furthermore, synchronization must not only be limited to time but also extend to space, entailing the sharing (synchronization) of spatial coordinate axes. This would be realized by three basic technologies, namely compact atomic clocks, wireless time synchronization, and cluster clock systems. The combination will eventually acquire sensing capabilities like distance measurement through radio wave propagation time.



Wi-Wi module

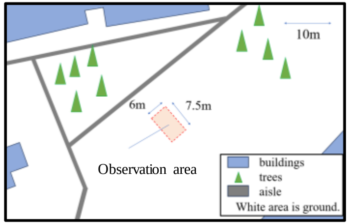


Records of clock reading in one day. Cluster clock (red curve) shows an enhanced stability, whereas ten thin curves are those of each clock.

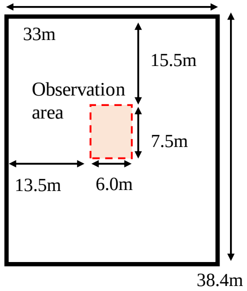
II-7 Experimental Evaluation of WLAN-based Device-Free Localization Using CSI in Outdoor and Large-scale Indoor Environments

Kyushu University, NTT Corporation

Wireless local area network (WLAN)-based device-free localization techniques using channel state information (CSI) have been investigated, where CSI feedback frames are collected and used as a dataset for machine learning (ML)-based localization. However, CSI-based localization scheme performance depends strongly on radio propagation environments such as the existence of reflective obstacles and WLAN antenna positions. This article introduces our recent studies with experimentation on WLAN-based device-free localization in outdoor and large-scale indoor environment scenarios. Experiment results confirmed that the developed localization scheme enhances the localization accuracy in specific areas effectively by properly positioning the access point (AP) and the terminal. We also discuss the degree to which performance difference is observed in various scenarios with different AP and terminal positions.

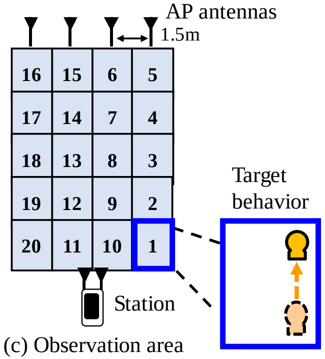


(a) Outdoor (university campus)



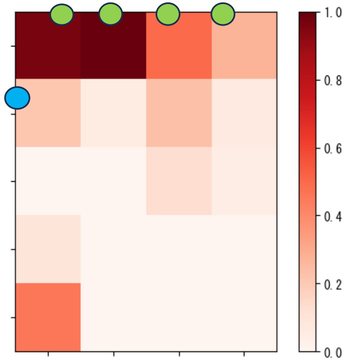
(b) Gymnasium

Number of antennas at AP	M=4
Number of antennas at STA	N=2
Antenna height	1m
Bandwidth	20MHz
Number of subcarriers	52

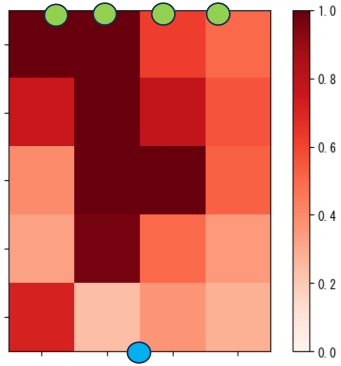


(c) Observation area

Experiment scenario and setup



Area-wise detection probability



Area-wise detection probability

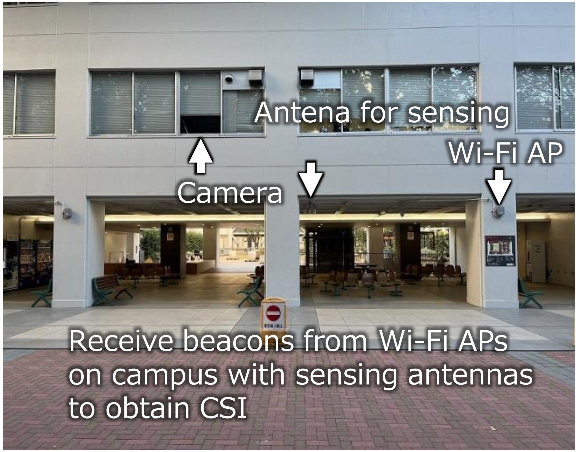
Average detection probability for large-scale indoor experiment scenario

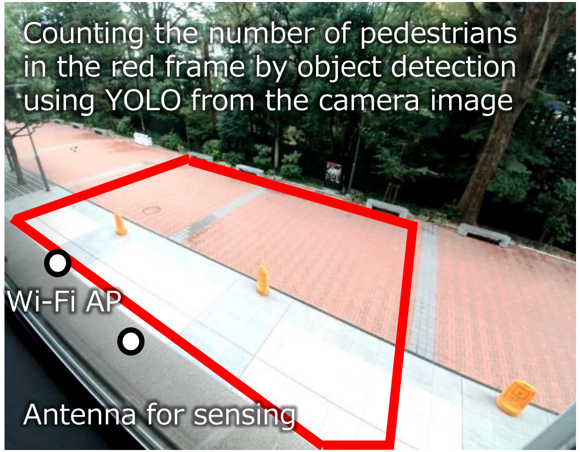
II-8

A Fundamental Study on the Relationship Between Pedestrian Traffic and Wi-Fi CSI with Existing Outdoor Access Points

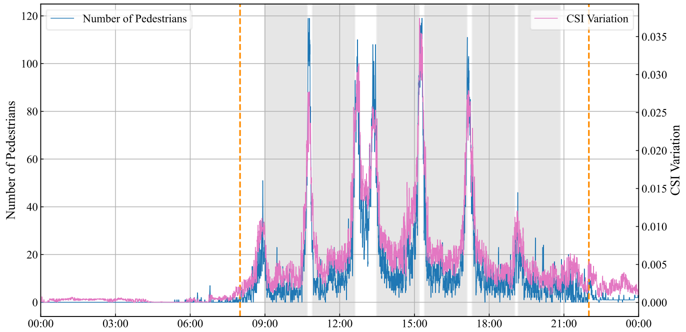
Sophia University

This article describes the relationship between pedestrian traffic and Wi-Fi channel state information (CSI) with existing outdoor access points (APs). Conducted on a university's main street, pedestrian traffic was measured using YOLOv8, and CSI variation was analyzed. The results show a correlation between CSI variation and congestion conditions, demonstrating the feasibility of estimating pedestrian traffic using CSI variation from existing Wi-Fi APs.





Measurement environment



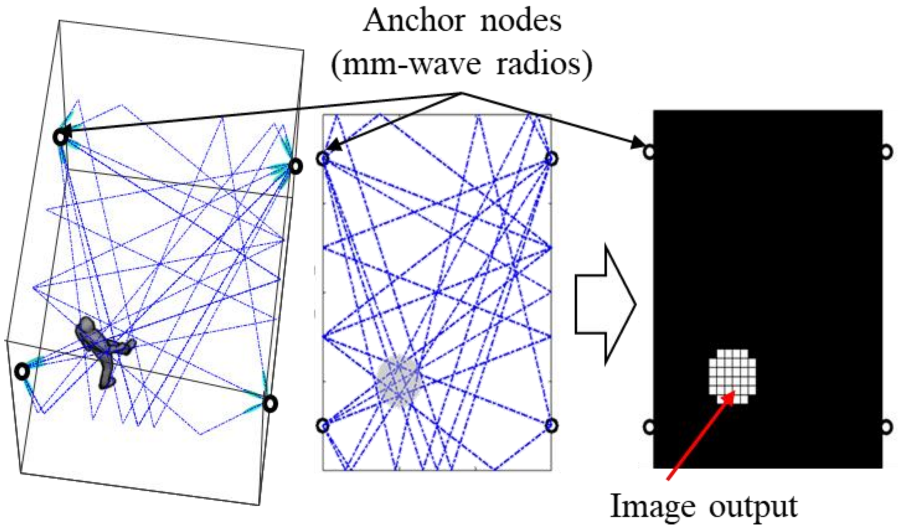
Number of pedestrians and CSI variation

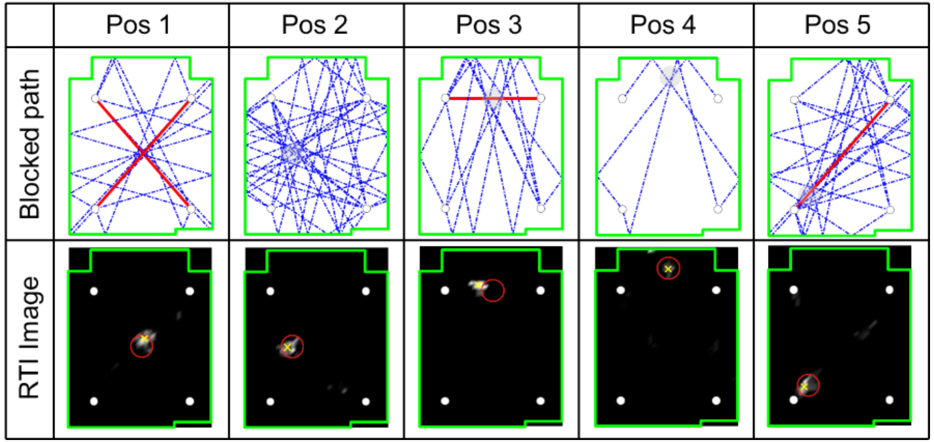
II-9

Multipath-RTI: Millimeter-Wave Radio Based Device-Free Localization

Niigata University

This work developed Multipath-RTI, a novel radio tomographic imaging (RTI) method utilizing millimeter-wave (mmWave) signals for device-free localization (DFL). Unlike conventional RTI approaches that struggle with multipath fading and require many physical anchor nodes, Multipath-RTI leverages virtual anchor nodes formed by multipath reflections. The study introduces compressed sensing-based image reconstruction, automatic parameter tuning, and DBSCAN clustering for multi-target location estimation. Results from simulations and mmWave channel sounding measurements show sub-0.5 m accuracy in complex indoor environments.



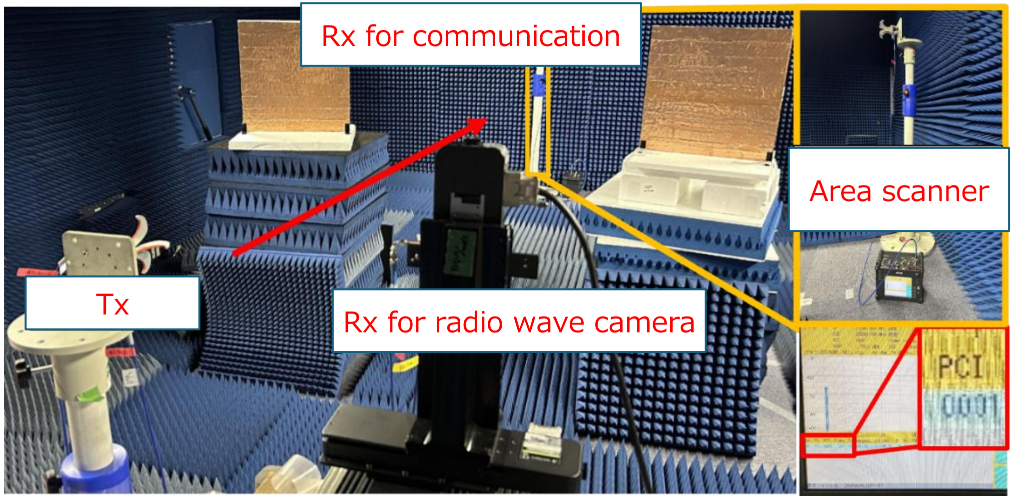


Measurement and evaluation

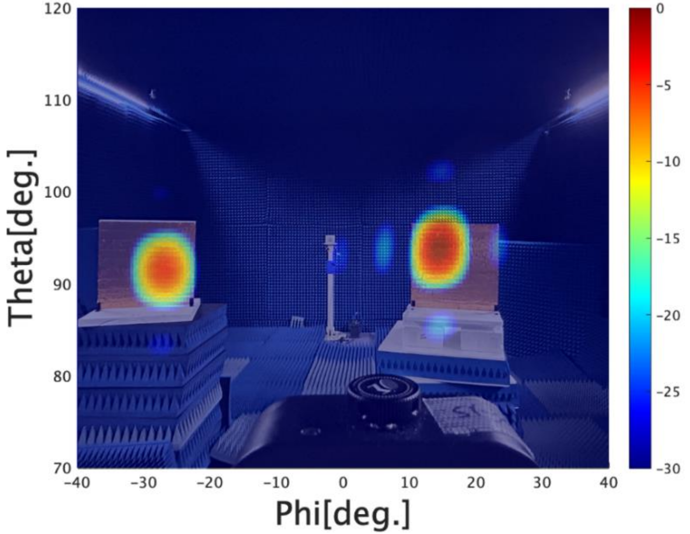
II-10 Verification in an anechoic chamber toward the realization of a radio wave camera using a mobile communication system

SoftBank Corp. Research Institute of Advanced Technology

As part of a preliminary study toward sixth-generation (6G) mobile communications, in which integrated sensing and communication (ISAC) is expected to be a key topic, the authors are investigating target direction estimation using reference signals embedded in a 3GPP-compliant waveform. This paper reports on measurements conducted in an anechoic chamber as part of a basic verification study. Specifically, a reflected 5G NR signal from the installed target is received using a virtual array antenna, and a direction estimation algorithm is applied to the demodulated reception characteristics. The results demonstrate that the target direction can be accurately determined.



Measurement environment



Measurement result