6G: Combining Communication and Sensing

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Slides are based on the work of Dr. Yang Miao

Contents

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Radio Systems @ UT

Electrical Engineering Discipline

9 staff members
~25 PhD students
3 PostDocs

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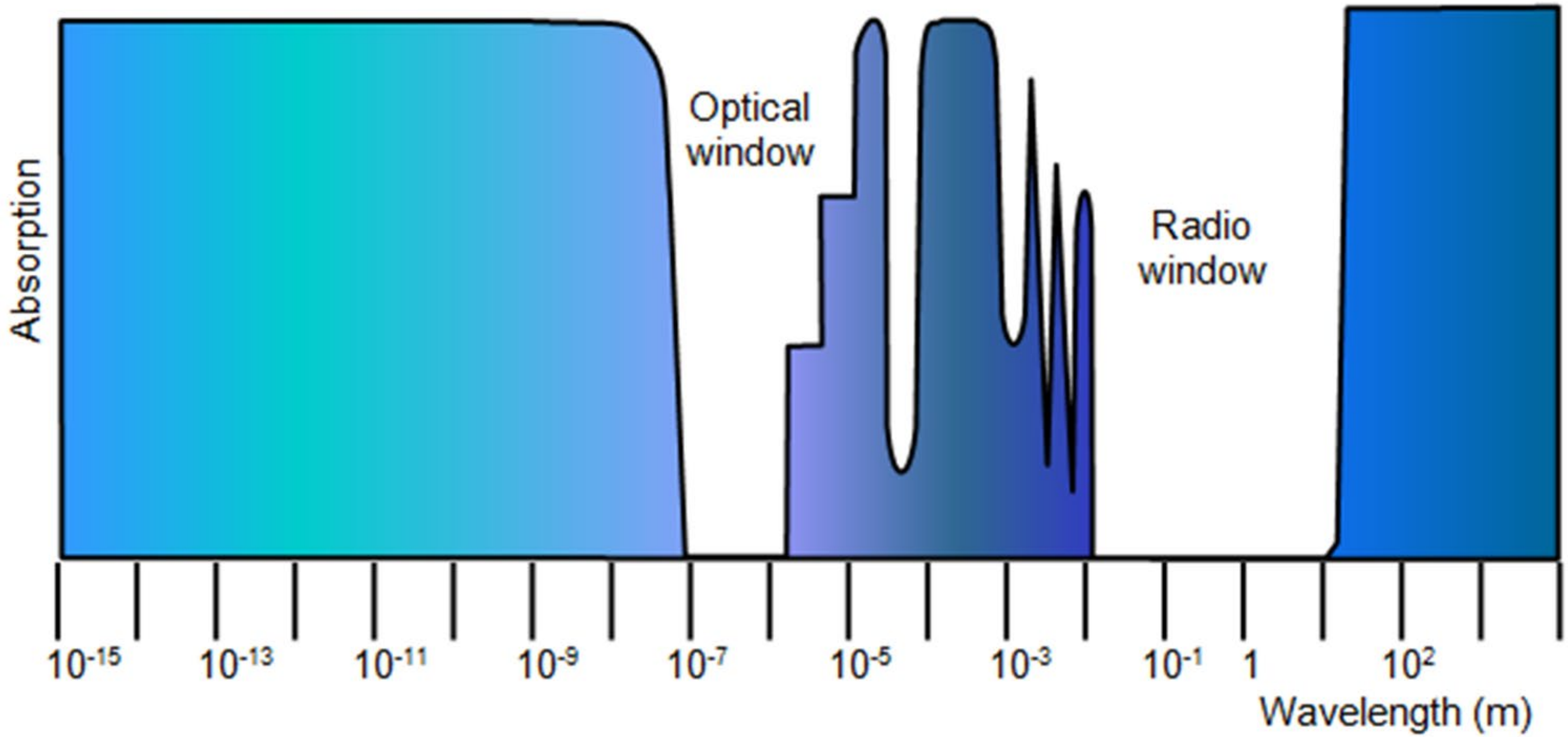
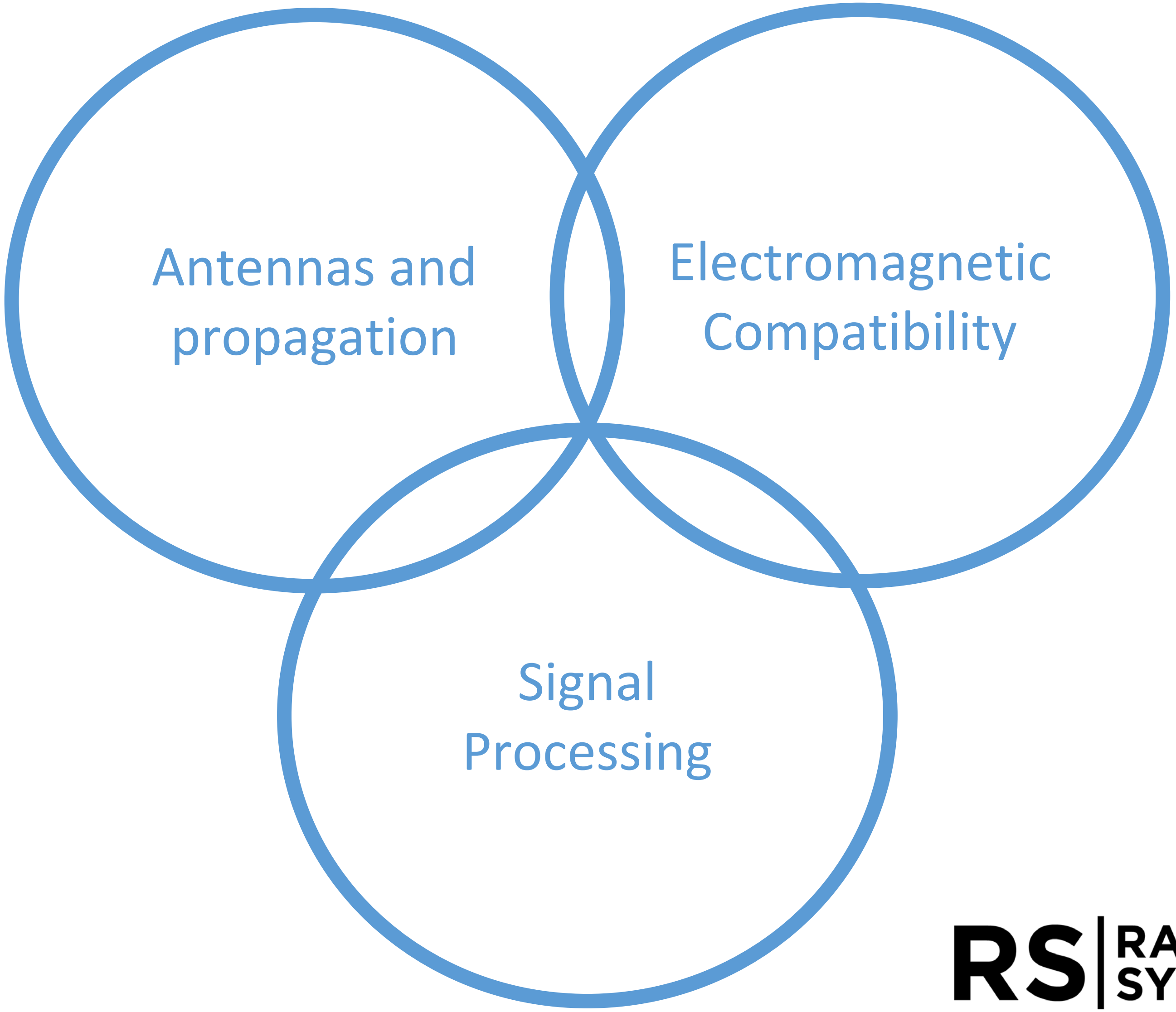
Radio Systems @ UT: What are Radio Systems?

Simplified overview of atmospheric absorption



From: https://www.schoolphysics.co.uk/age16-19/Wave%20properties/Wave%20properties/text/Atmospheric_absorption/index.html

Radio Systems @ UT



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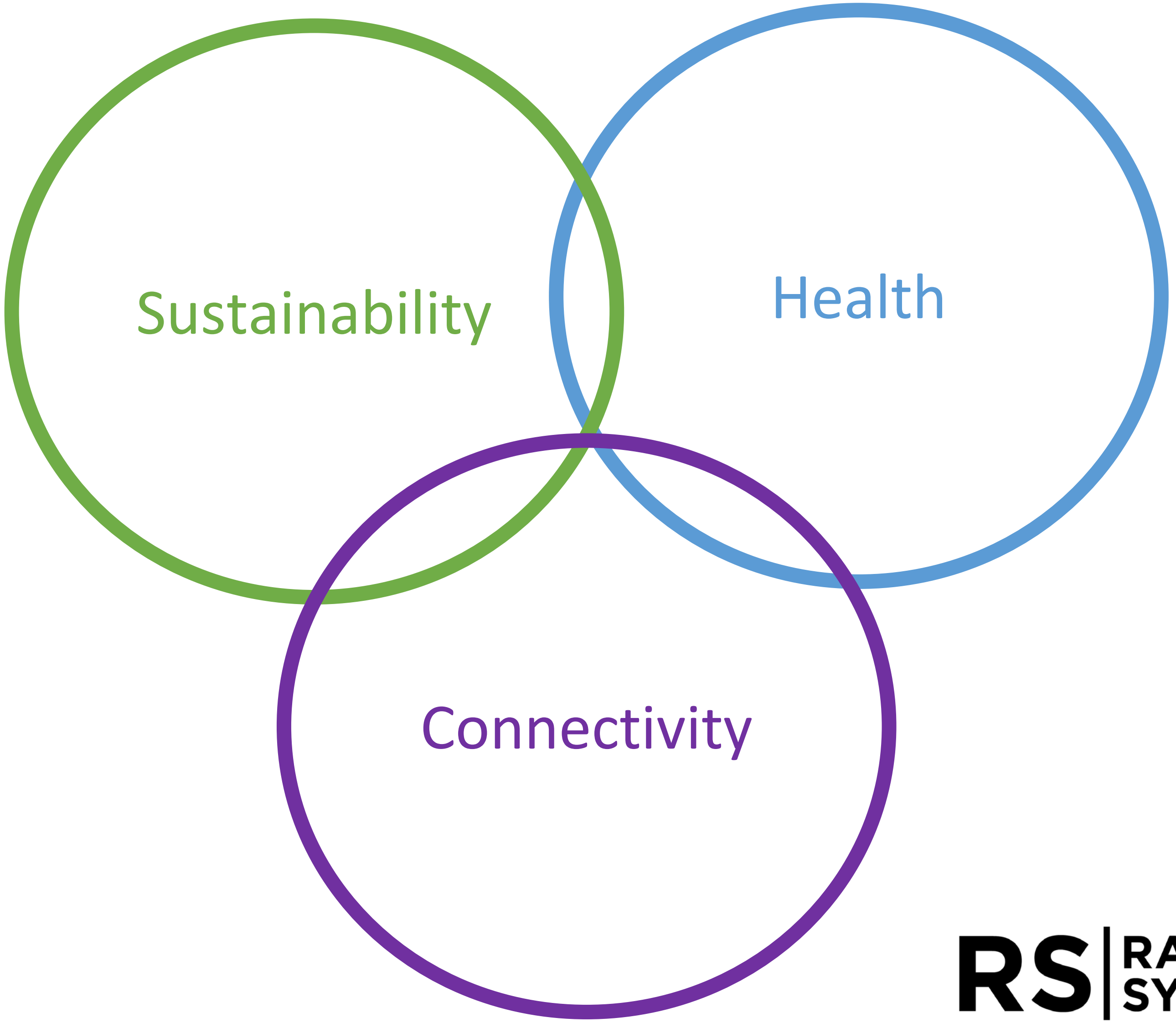


5G/6G Developments

5G:

- Enhanced mobile broadband
  - FR1: Sub-6GHz
  - FR2: 24-27 GHz (mmWave)
- Massive Machine-type Communications (mMTC)
- Ultra-Reliable Low-Latency Communications (URLLC)

6G

- Frequency bands
  - FR3: 7-24 GHz
  - Sub THz / THz: 95 GHz – 3 THz

5G/6G Developments

Higher frequencies and more bandwidth for communication =>

- reduces the dimension (or space) of the antenna array for a given angular resolution. Alternatively, more antennas could use the same space to increase angular resolution, which is beneficial for UE and for the base station.
- leads to more directional signals with less multipath components
- leads to larger Doppler shifts for the same target velocity

5G/6G Developments

Higher frequencies and more bandwidth => Radar

- reduces the dimension (or space) of the antenna array for a given angular resolution. Alternatively, more antennas could use the same space to increase angular resolution, which is beneficial for UE and for the base station.
- leads to more directional signals with less multipath components
- leads to larger Doppler shifts for the same target velocity
- achieve higher range accuracy and resolution due to the availability of a larger signal bandwidth

What is 'Joint Communication and Sensing'?

Different levels of combining 'Communication' and 'Radar (Sensing)'

- Sharing frequency bands
- Combining sites

} Cooperation (loose integration)

- Dynamic sharing of
  - Waveforms
  - Hardware resources
    - Antennas
    - Processing capacity

} Codesign (tight integration)

What is 'Joint Communication and Sensing'?

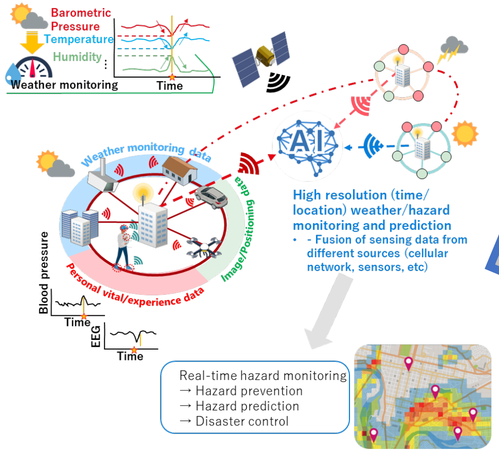
Use cases ETSI

- Approved 18 use cases with their corresponding 6G System requirements
- Identified impacts on channel modelling, RAN and system architecture, and privacy, security, trustworthiness and sustainability issues
- Consolidated potential requirements and key performance indicators
- Example - Human motion recognition:

    Motions/Gestures/Postures => different amplitude and duration => different requirements for accuracy, update rate, latency to sensing equipment

The following 4 slides are from ETSI

Public Health and Safety

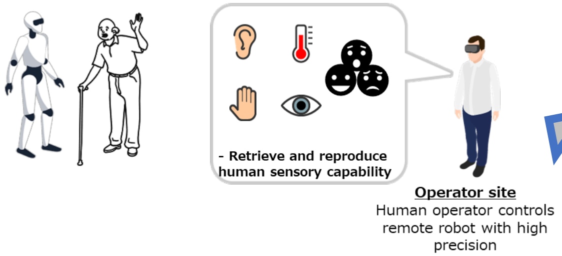


Real-time monitoring of health hazard and disaster risk

- Hazard monitoring, disaster area prediction, disaster control, realtime hazard map for first responder intervention

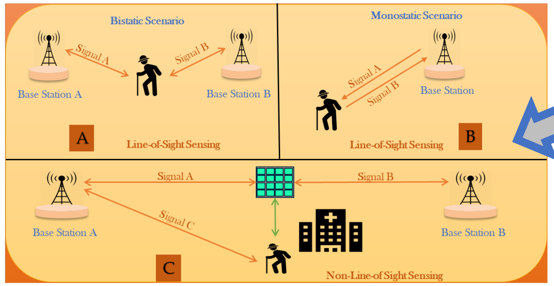
Emergency search and rescue

- UE based detection of survivors in emergency situations, in and out of coverage



Remotely controlled robots for senior citizen monitoring and care

- Elderly care remotelly controled robot for companionship and health monitoring

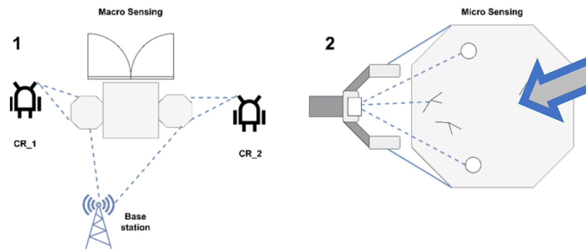


Outdoor healthcare sensing and monitoring

- Health monitoring, public health management, emergency alert

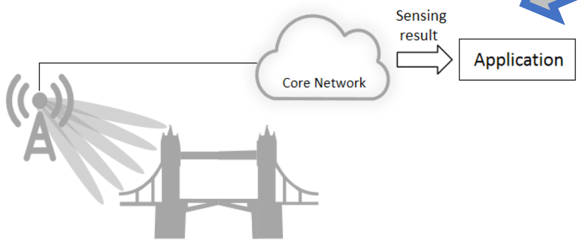
Slide from ETSI

Factory automation, infrastructure monitoring



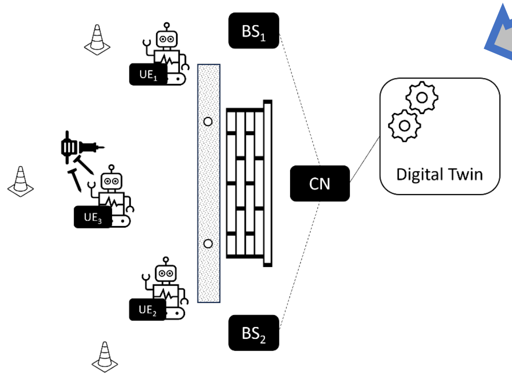
Precise localization for robot grasping

- Determine grasping points through micro and macro sensing



Micro-deformation sensing

- Infrastructure safety monitoring



Collaborative robots based on digital twinning

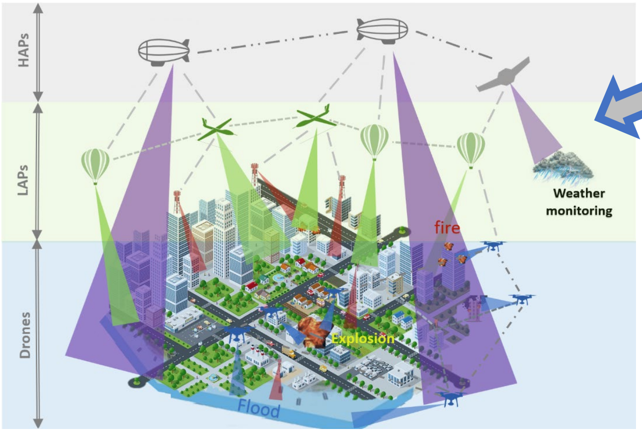
- In-factory autonomous robots based on digital twinning

Realtime cyber-physical systems in industrial worksites

- In-factory work management, remote control, human-robot interactions

Slide from ETSI

Environment reconstruction, XR, entertainment, network operation support



Airborne-based sensing for environmental reconstruction

- Environment reconstruction for emergency and rescue, traffic control

High resolution topographical maps

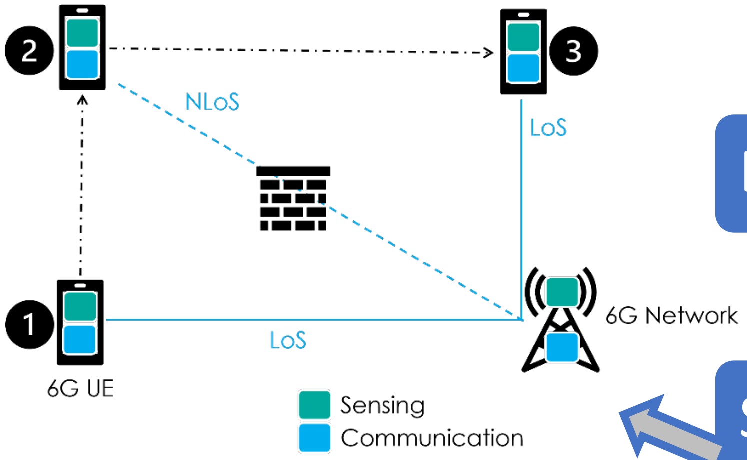
- High-resolution topological or environmental map for a specific area

Human motion recognition

- Immersive interaction, sports monitoring with large scale and small scale motion recognition

Body proximity sensor

- Transmission power control and beam management based on human target detection

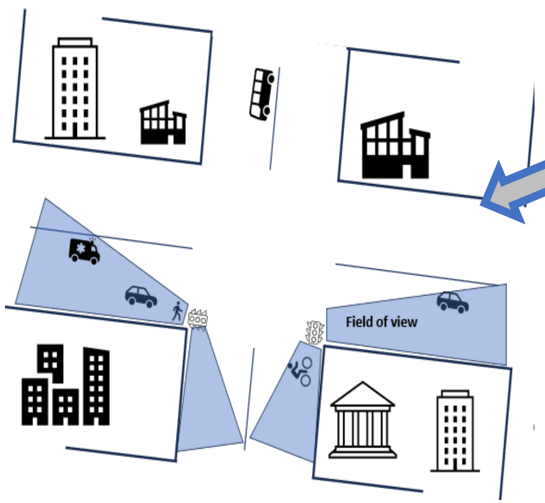


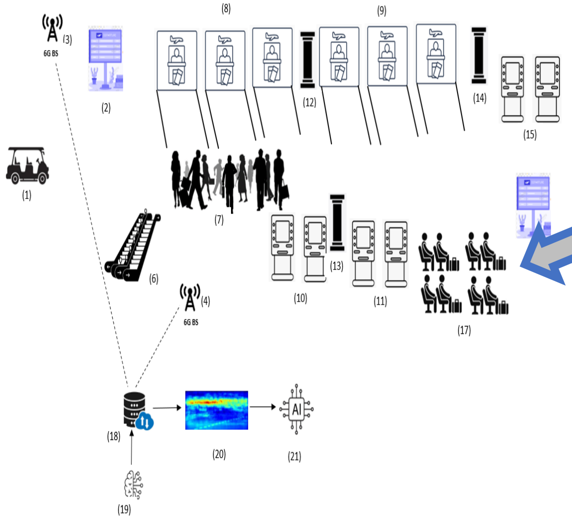
Sensing-aided communications

- Enhanced network performance and efficient use of resources

Slide from ETSI

Ground and Aerial Vehicles (Automotive, UAVs)





Traffic throughput and safety on road intersections

- Traffic management, road safety

Use case on safe & economic UAV transport

- Flight path control, intrusion detection, collision risk mitigation

Use case on emergency vehicle route planning

- Route planning optimization, first responder support, digital twin

Use case for automated guided vehicles travelling in airports

- AI-enables passenger service, environment mapping

Vison-aided sensing

- Computer vision aided smart traffic management

Slide from ETSI

Requirements vs Reality of CURRENT NETWORK

Use cases	Requirement	Current	Gap
Industrial robotics (indoor positioning / digital twins)	<30 cm indoor positioning; reliable NLOS sensing; scalable maps & coordination [ETSI ISG ISAC GR ISC 001; 3GPP TS 22.872; Rel-17 NR positioning enhancements; Rel-18 e-Positioning]	• NR PRS/SRS: ~1.9–3 m LOS, ~8–11 m NLOS (sim/lab) • cm-level only in research setups with carrier-phase & tight sync [NR PRS/SRS positioning evals — MDPI *Applied Sciences* 2025; 3GPP Rel-17/18 positioning studies]	• Order-of-magnitude accuracy gain in real NLOS • Robust operation in multipath/occlusion • Integration into digital-twin frameworks, real-time
Mobility (V2X / cooperative perception)	<50 ms E2E latency; <20 cm localization; robust cross-node fusion [3GPP TS 22.186; Rel-17/18 positioning for V2X]	• NR sidelink PHY: ~10–20 ms • mmWave best-case sub-ms PHY latency is rare • Typical E2E offloading: ~47–90 ms • Positioning error: ~1–3 m LOS, >7 m NLOS [Fezeu et al., PAM 2023: mmWave PHY latency ; 5G mmWave E2E offloading pipelines (edge inference)]	• Stable <50 ms E2E under mobility • Sub-20 cm accuracy at scale • Reliable fusion across moving nodes
Contact-free health monitoring	<1 bpm breathing error; <3 bpm HR error; robust through clothing/obstructions; reliable in motion [ISO/IEC monitor specs; ETSI GR ISC 001]	• mmWave JCAS/FMCW: ~0.4–1 bpm BR error; 2–10 bpm HR error (lab, ≤3 m) • Accuracy degrades with clothing, blankets, motion • Not clinically validated [mmWave JCAS/FMCW health sensing demos (lab conditions)]	• Clinical-grade validation missing • Robustness in motion, occlusion, longer range • Multi-target separation • Privacy & data governance frameworks

What is 'Joint Communication and Sensing'?

Why RF Sensing and not using camera's?

- Light conditions not always guaranteed
- No additional infrastructure (camera's)
- Privacy

What is ‘Joint Communication and Sensing’?

Challenges

- Schedule suitable sensing resources, provide sensing results of (multiple) sensing tasks (in a specific time window)
  - Trade-offs between communication and sensing under Aperture-Band-Time limited resources
  - Efficient (e.g., overhead) yet effective (e.g., accuracy) resource allocation for dynamic situations
- System robustness and costs
  - Selectivity/linearity (distorted sub-band signals); quantization, array, etc. hardware imperfection
  - Power/energy consumption, number of components
  - Computation/processing speed and power consumption
    - E.g., time consumption for beam scanning
  - Carbon footprint & sustainability, e.g., material
  - EMF exposure
  - Physical Layer Security

What is ‘Joint Communication and Sensing’?

Challenges

- Channel Models
  - Why Channel Models
    - System design & network planning, deployment and optimization
    - Testing & measurement
    - Standardization
    - Machine learning and AI supported Systems
  - Criteria
    - Accuracy
    - Complexity
    - Generality
  - Issues
    - Time variance
    - Near Field / Far Field

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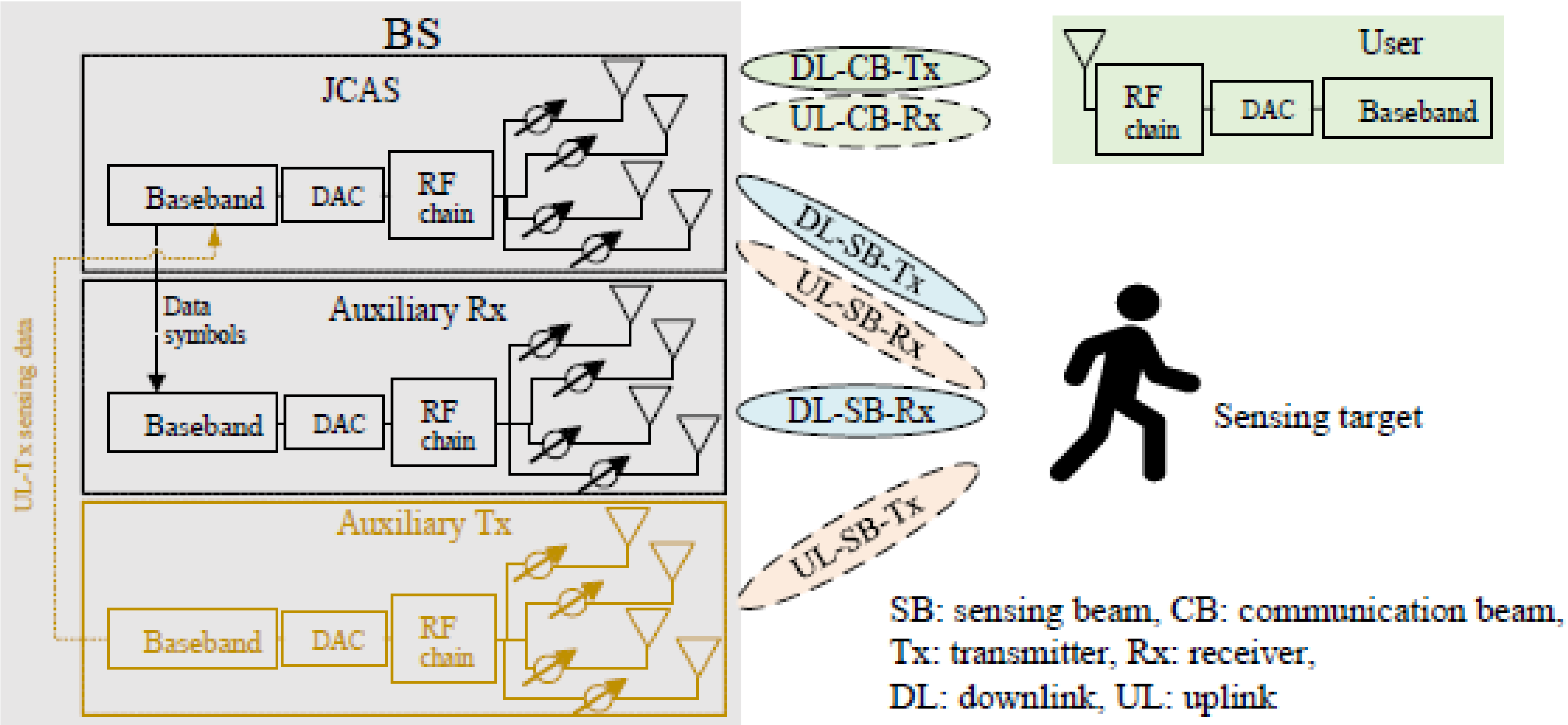

Figure 3.1: The configuration for JCAS in BS.

Alidoustaghdam, H., Kokkeler, A., & Miao, Y. (2023). Sparse Tiled Planar Array: The Shared Multibeam Aperture for Millimeter-Wave Joint Communication and Sensing. Electronics, 12(14), 3115. https://doi.org/10.3390/electronics12143115

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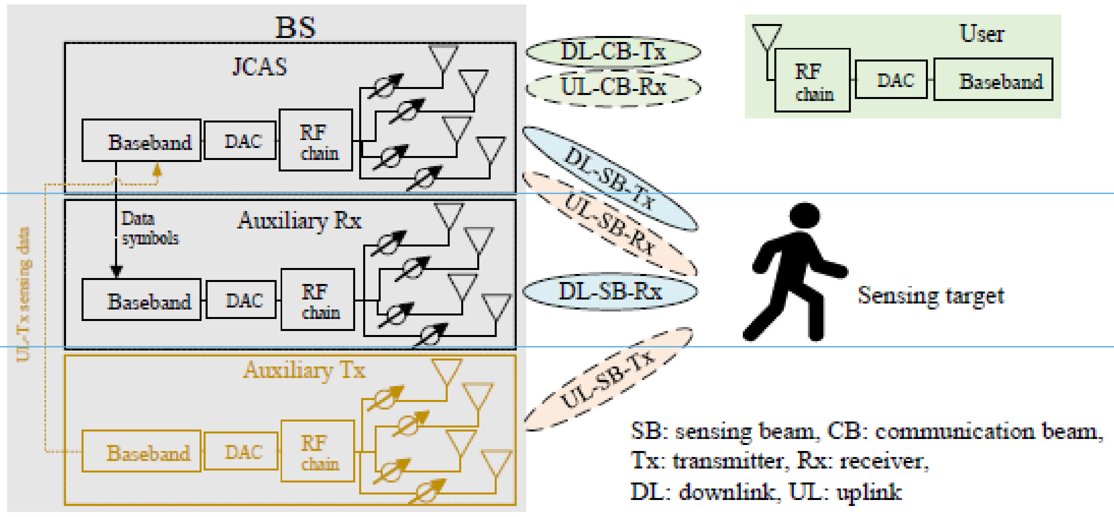

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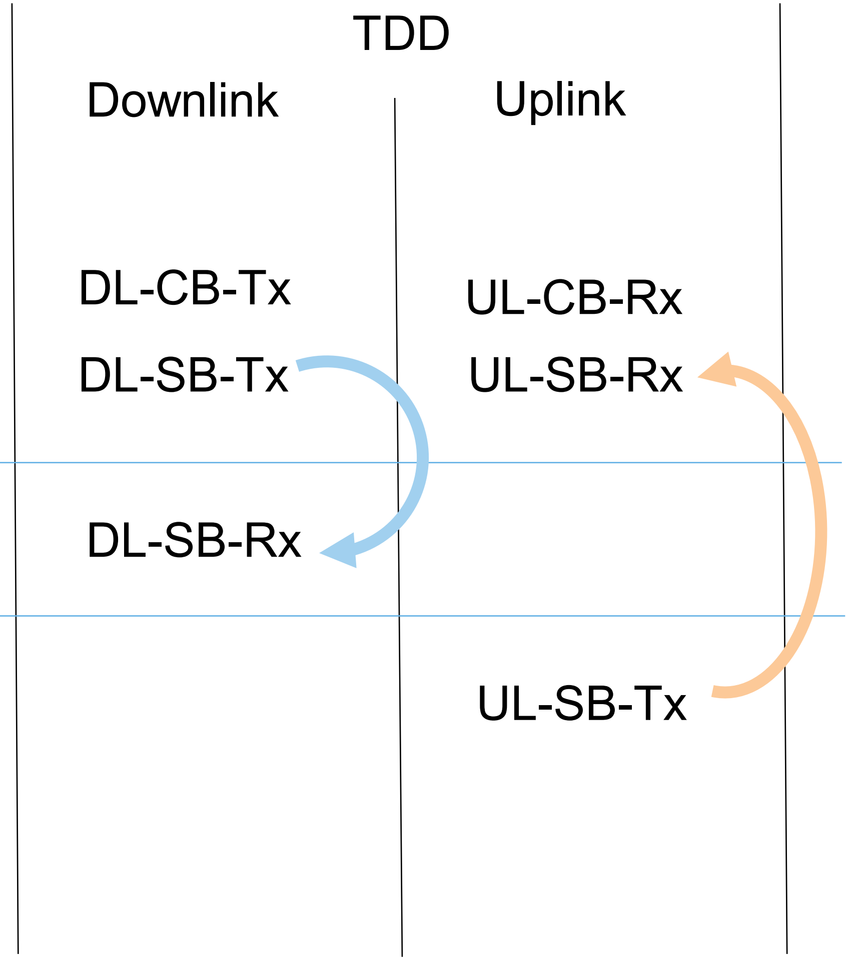

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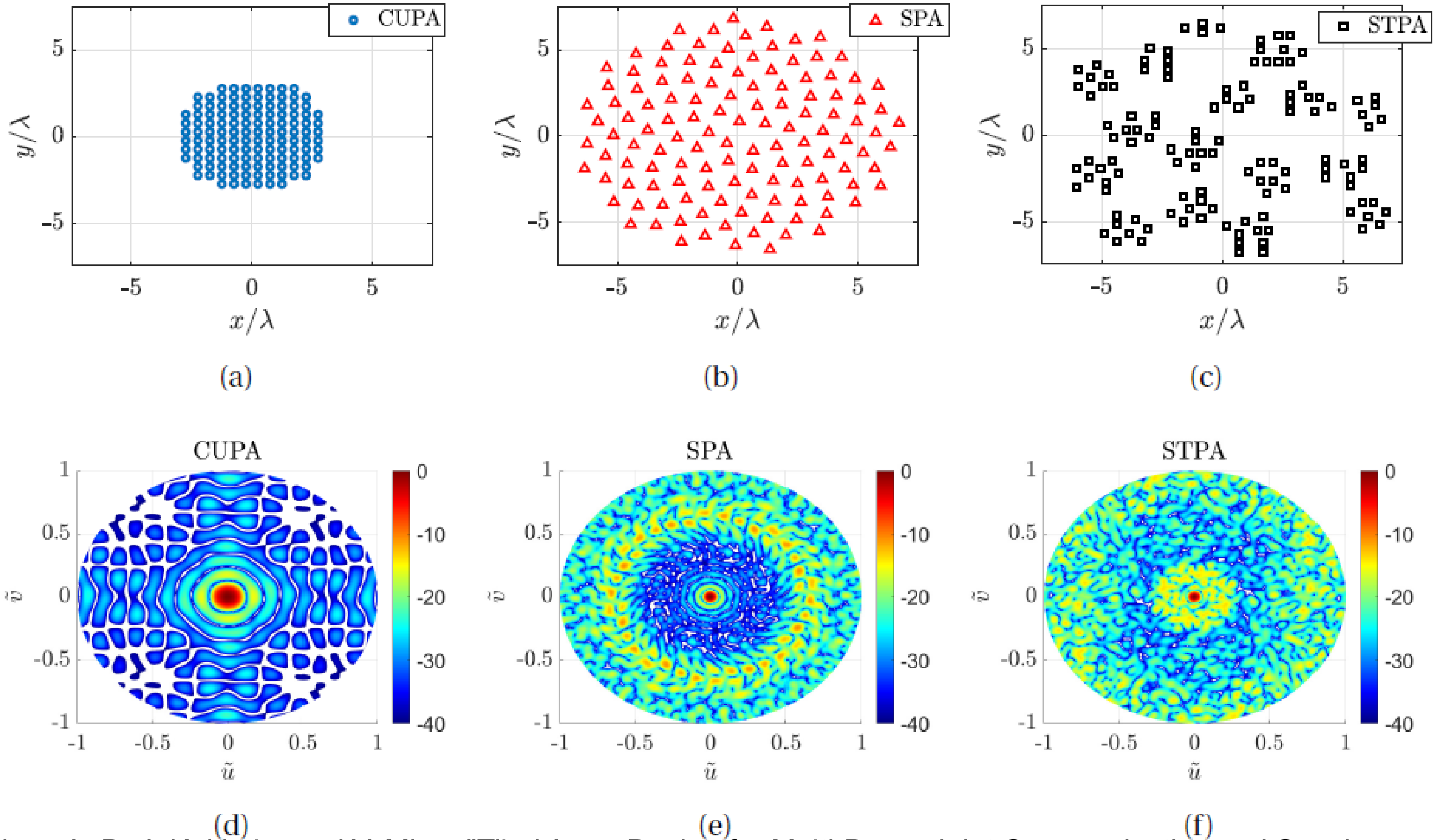

H. Alidoustaghdam, A. B. J. Kokkeler and Y. Miao, "Tiled Array Design for Multi-Beam Joint Communication and Sensing: Channel Matching Method," in IEEE Open Journal of the Communications Society, vol. 6, pp. 8477-8495, 2025, doi: 10.1109/OJCOMS.2025.3616790.

Credits to Hadi Alidoustaghdam

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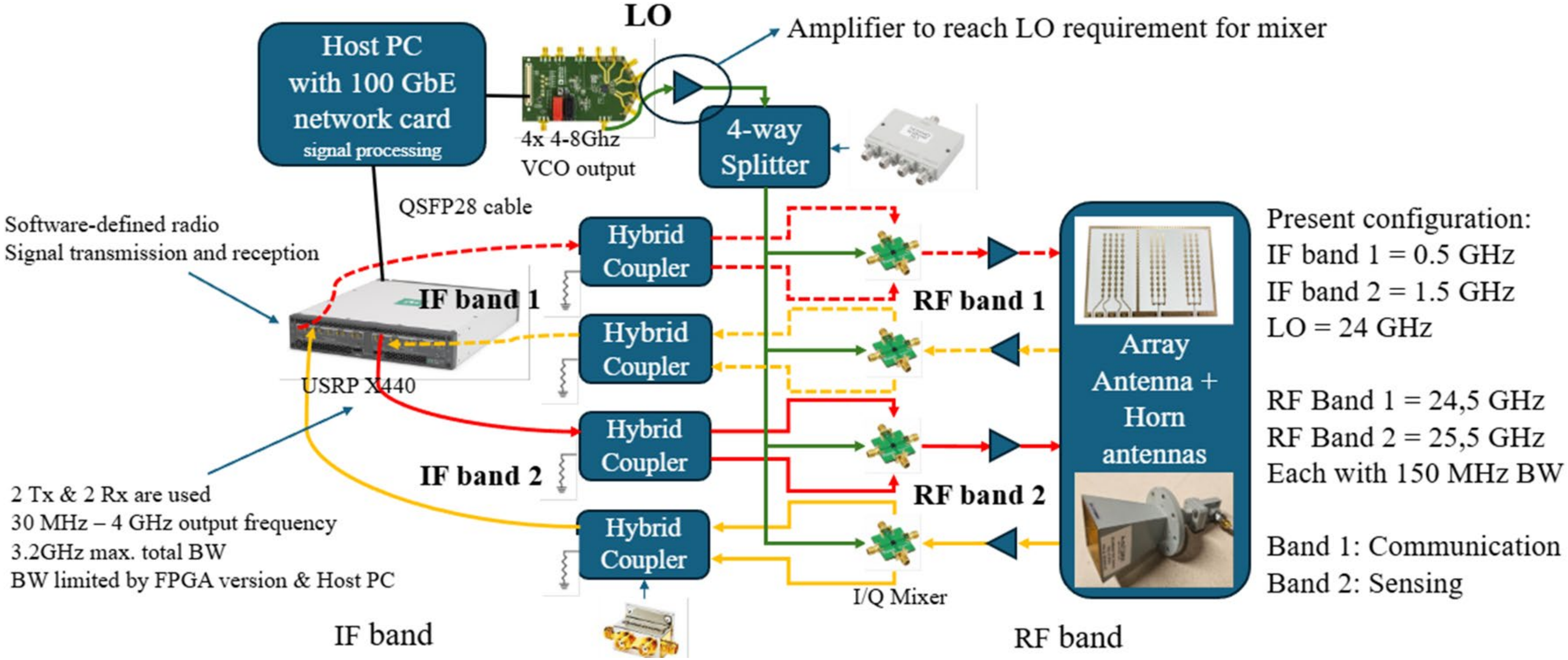
B. Yan, A. B. J. Kokkeler and Y. Miao, "A Multi-Band Full-Duplex Prototype for Integrated Sensing and Communication," 2025 55th European Microwave Conference (EuMC), Utrecht, Netherlands, 2025, pp. 1207-1210, doi: 10.23919/EuMC65286.2025.11235254.

An ISAC BS Implementation Example



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- Channel sounding SOTA
  - Need to know groundtruth
  - Camera, LiDAR + channel sounder
    Spatially and temporally synchronized

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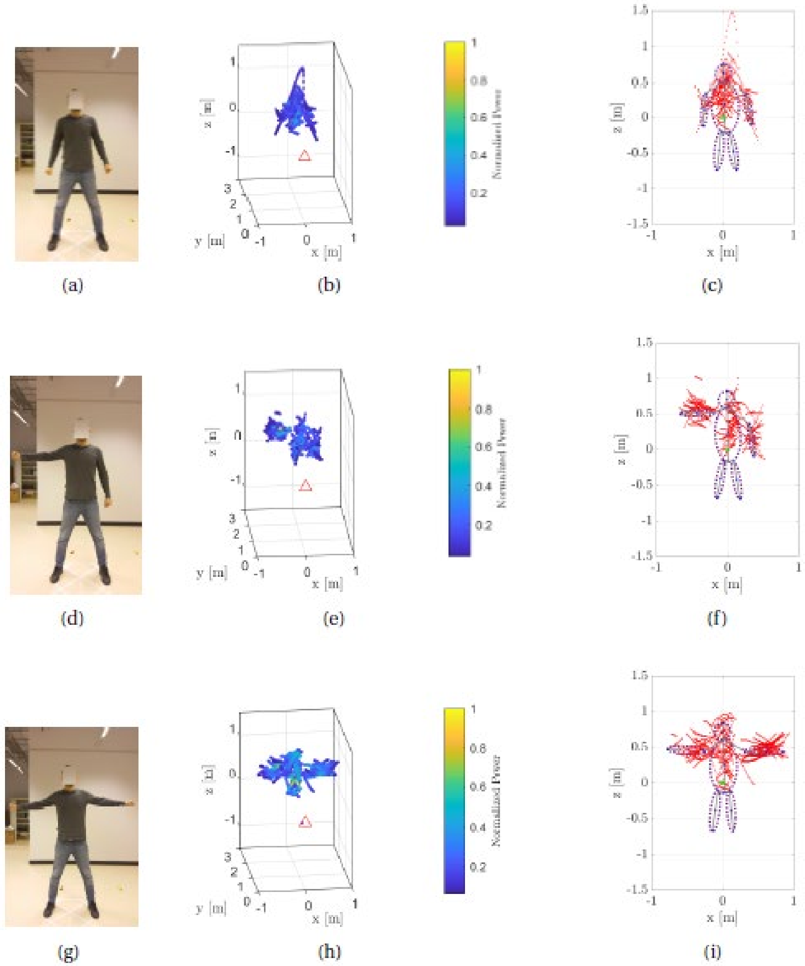

H. Alidoustaghdam, M. Chen, B. Willetts, K. Mao, A. Kokkeler and Y. Miao, "Enhancing Vital Sign Estimation Performance of FMCW MIMO Radar by Prior Human Shape Recognition," *2023 IEEE International Conference on Communications Workshops (ICC Workshops)*, Rome, Italy, 2023, pp. 1707-1711, doi: 10.1109/ICCWorkshops57953.2023.10283718.

Experiments @ 77-80.6 GHz

Credits to Bixing Yan

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More general problem formulation: Joint optimization of resource allocation

Requirements:

- Communication
- Sensing

Trade-offs:

- Time
- Frequency
- Space
- Power

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More general problem formulation: Joint optimization

Maximize communication Spectral Efficiency

Subject to

- Required sensing constraints
- Communication user fairness constraints
- Maximum transmit power constraints

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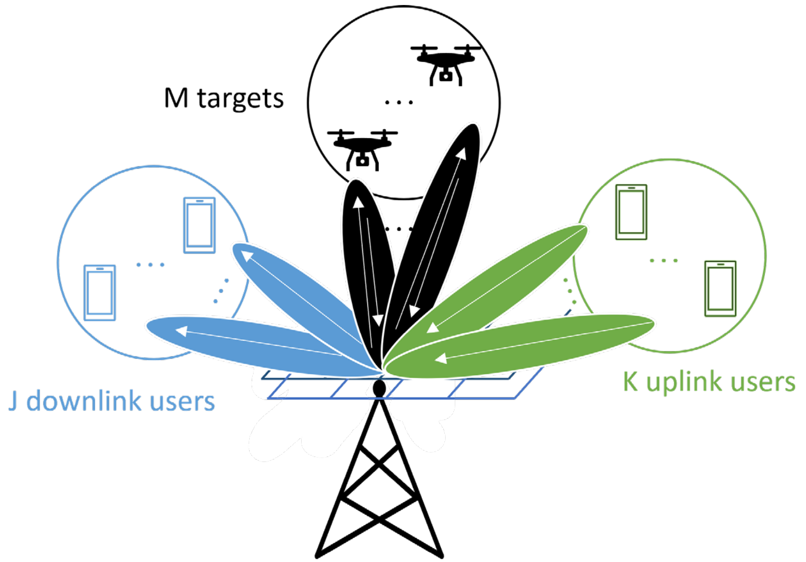
Numerical simulation

Parameter	Value
Num of antennas Nt = Nr	32
Num of downlink users	2
Num of downlink users	2
Num of targets	2
Center frequency	39 GHz
Bandwidth (within one sub-band)	10 MHz
Pmax	17 dBW
Distance of users to BS	250 m
Distance of targets to BS	100 m
Channel realization	200

Credits to Dao Duc Nguyen

D. N. Dao, H. Zhang, A. B. J. Kokkeler and Y. Miao, "Joint Beamforming for Multi-user Multi-target FD ISAC System: A Hybrid GRQ-GA Approach," 2025 IEEE Wireless Communications and Networking Conference (WCNC), Milan, Italy, 2025, pp. 1-6, doi: 10.1109/WCNC61545.2025.10978123.



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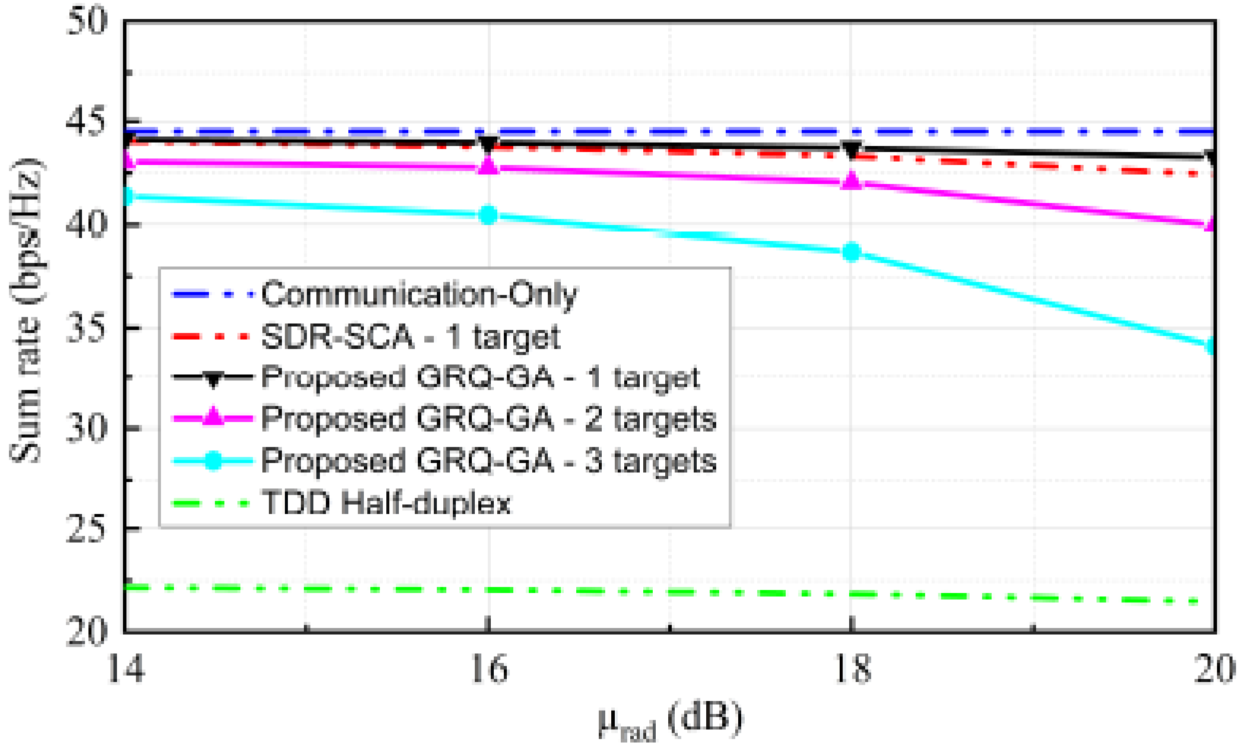

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Credits to Dao Duc Nguyen

Conclusion

- Combining communication with sensing functionality is one of the major innovations for 6G
- Broad range of applications
- Multi-dimensional optimization challenge:
  - Frequency <-> Time <-> Space <-> Power/Energy <-> Sensing Sensitivity <-> Communication Capacity <-> Antenna Array configurations <-> Processing Capacity

Dank voor uw aandacht