Integrated Communication and Sensing:
Challenges, Current Trends and Future Directions

Wireless Knowledge Summit 2022

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Outline

1. Sensing
2. Challenges
3. Current Trends
    a. WiFi
    b. Cellular
4. Future Directions

Sensing

- Overview
- Uses Cases
- Terminologies
- Technologies
- Summary

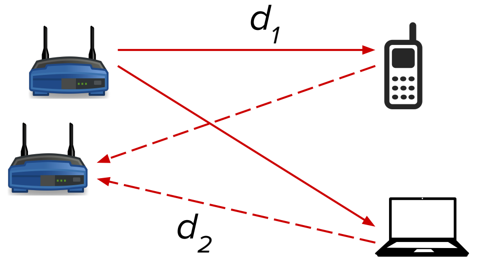
Sensing

- Any kind of detection, estimation and tracking
- Parametric and non-parametric
- Key parameters - variation in propagation channel
    a. CSI
    b. AoA & DoA
- ICaS - *One radio to rule them all*

Uses cases

- Spectrum sharing and efficient utilization
- Typical
  - Localization and positioning - navigation, velocity estimation, GPS-denied area
  - Occupancy detection - presence/count detection, appliance control
  - Motion tracking - beam tracking, camera focus, surveillance
- Upcoming
  - Environment mapping - IoT/Robot/car/SLAM/digital twins/V2X
  - Gesture recognition - Appliance control
  - Health care - Fall detection, vitals monitoring

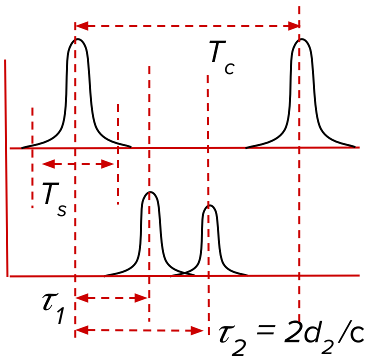
Terminologies



Range Resolution

$cT_s / 2 = c / 2B_s$

Maximum Range $cT_c / 2$



Single pulse over time

Carrier frequency	∝	**1 / Vmax**
	∝	**1 / Vres**
	∝	**1 / Ares** *
	∝	**FoV**
Bandwidth	∝	**1 / Rres**
Pulsing interval	∝	**Rmax**
	∝	**1 / Vres**
	∝	**1 / Vmax**
# of Rx antennas	∝	**1 / Ares** *

Phase difference of two pulses over time: $2\pi f_c(\tau_{T2} - \tau_{T1}) = 4\pi(d_{T2} - d_{T1})/\lambda$

Dividing by T_c, we get: $4\pi v/\lambda$

For N discrete samples in T_c,

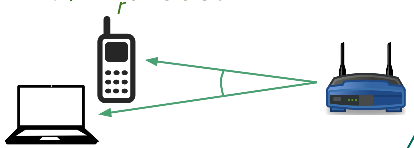
Velocity Resolution $\lambda/2NT_c$

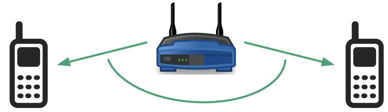
Maximum Velocity $\pm \lambda/4T_c$

Single pulse over space

Angular Resolution *

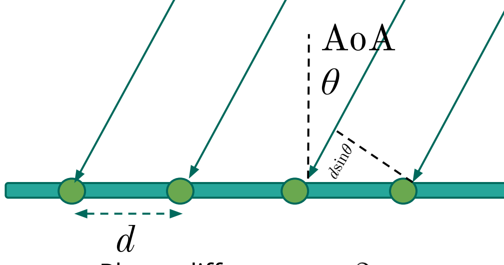
$\lambda / N_r d \cos\theta$





Field of view

$\mp \sin^{-1}(\lambda / 2d)$



Phase difference (across spatial streams) $= \dfrac{2\pi}{\lambda} d \sin\theta$

* Non-uniform: Varies with AoA

Examples

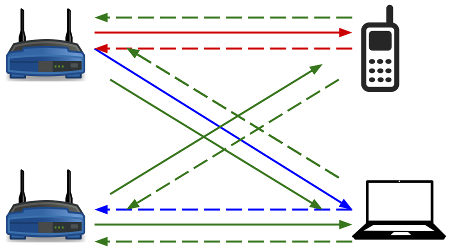
Fc (in GHz)	Resolvable velocity	Maximum velocity (±)	Applicable in
~ 2.4	25 kmph	1350 kmph	802.11, 4G, 5G
5	~ 10 kmph	~ 810 kmph	802.11ac, 4G, 5G
28	~ 2.5 kmph	~ 144 kmph	5G FR2
60	~ 1 kmph	~ 68 kmph	802.11ad

Fc	Angular Resolution	Rx Antennas
2.4 GHz	15°	4
5 GHz	7°	4
28 GHz	0.5°	64

Bandwidth (in MHz)	Resolvable object size	Applicable in
20	7.5 m	802.11n, 4G
80	1.875 m	802.11ac, 5G
400	37.5 cm	5G FR2
2000	7.5 cm	802.11ad

Technologies

- Monostatic, bi-static, multi-static
- Time or frequency domain processing
- Pulse/Chirp/OFDM - radars
  - Analog (pulse/chirp) & Digital (OFDM)
- Clutter removal (stationary background)
- Delay-Doppler processing (FFT along time not along delay)
- Beamforming and tracking



Summary of Sensing

- Different uses cases
- Parameters: Resolution & max of *range, speed & AoA*
- Radar types and waveforms
- Assumptions:
    a. Synchronization
    b. Homogeneous reflectivity
    c. Object size > wavelength
    d. Clutter is stationary

Challenges

Systems

Algorithms

Hardware

Summary

Systems

- Scheduling
  - Effect of URLLC scheduling protocols on ICaS?
- Full CSI - time/space/frequency
- Minimizing feedback overhead in uplink
- Modeling non-homogenous channels
- Guard interval placements
- Legacy support

Algorithms

- Signal processing for non-stationary geometries
  - Need retraining and robust model learning
- Dense deployments - pilot/pulse contamination
  - Need central coordination and orchestration
- Interference cancellation
  - Need sophisticated processing at UE
- Data fusion
  - Data from past: low-memory-algorithms for tracking
  - Fuse echoes from multiple targets and sources

Hardware

- Multi-band antennas - *aperture size ∝ SNR ∝ clutter reduction*
- Non-linear, compact phased arrays - *beam scanning*
- ADC with large number of RF chains - *angular resolution*
- Fast switches - *frequency/space multiplexing*
- High frequency PLL - *sensing resolution is phase sensitive*
- Full duplex - *self interference cancellation*

Summary of Challenges

- Optimal scheduling and synchronization techniques
- Minimizing time/space/frequency CSI/feedback
- Minimizing/cancelling interferences
  - From self and neighbors
- Robust channel modeling/learning/tracking
- Sensitive PLL for high frequencies

Current Trends

IEEE 802.11bf

5G/6G

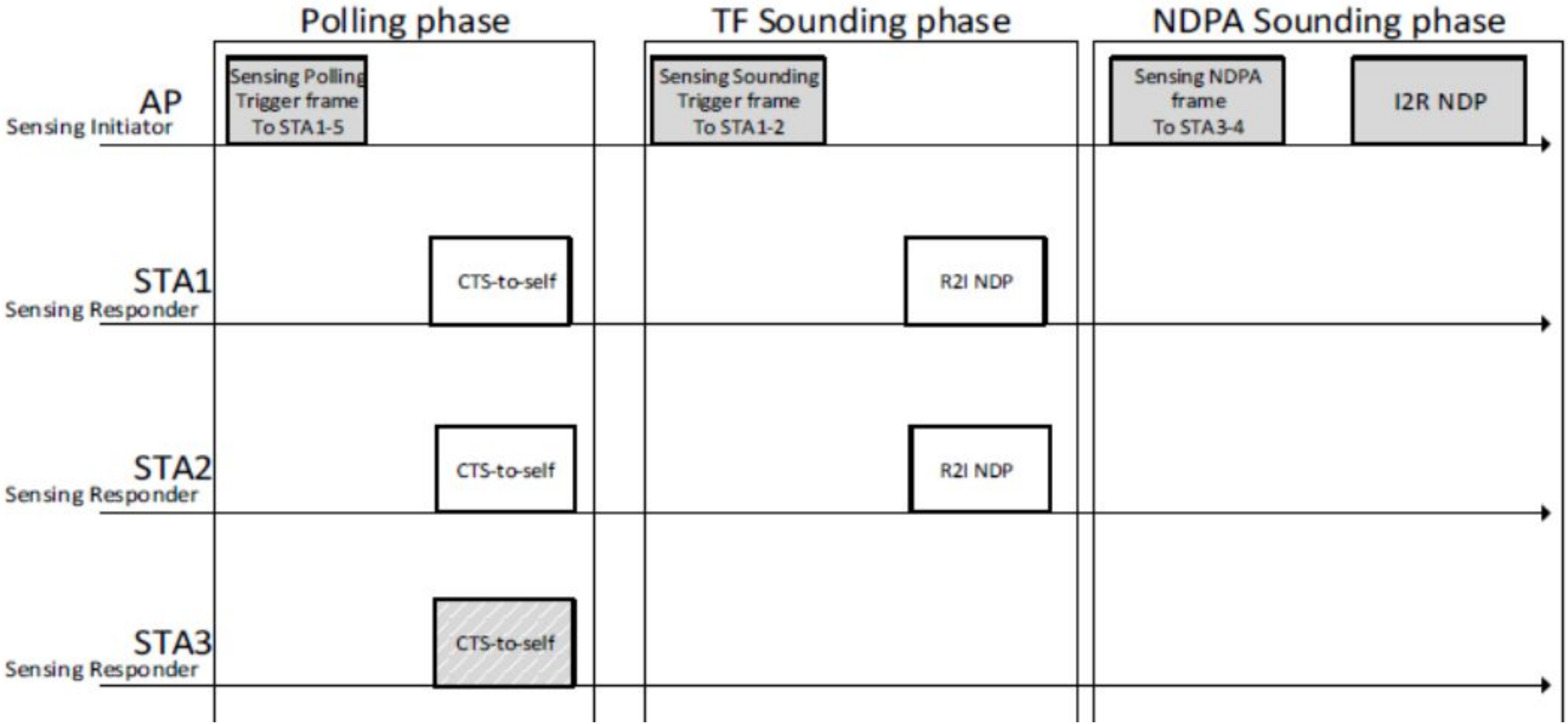
IEEE 802.11bf

- An amendment that enables devices to
    - Request sensing
    - Transmit sensing packets (NDP) and feedback
    - MAC interface to request/retrieve sensing measurements
- Measurement processing is left to OEM
- Focus: Directional Multi Gigabit (DMG)
    - MAC: WiGig and sub-7 GHz bands PHY: Only WiGig
    - MAC: Scheduling, initiating and responding protocols
    - PHY: CSI quantization/grouping, power control, hi-BW NDP format
- (E)DMG: Multiple beam/burst allowed for 3D imaging

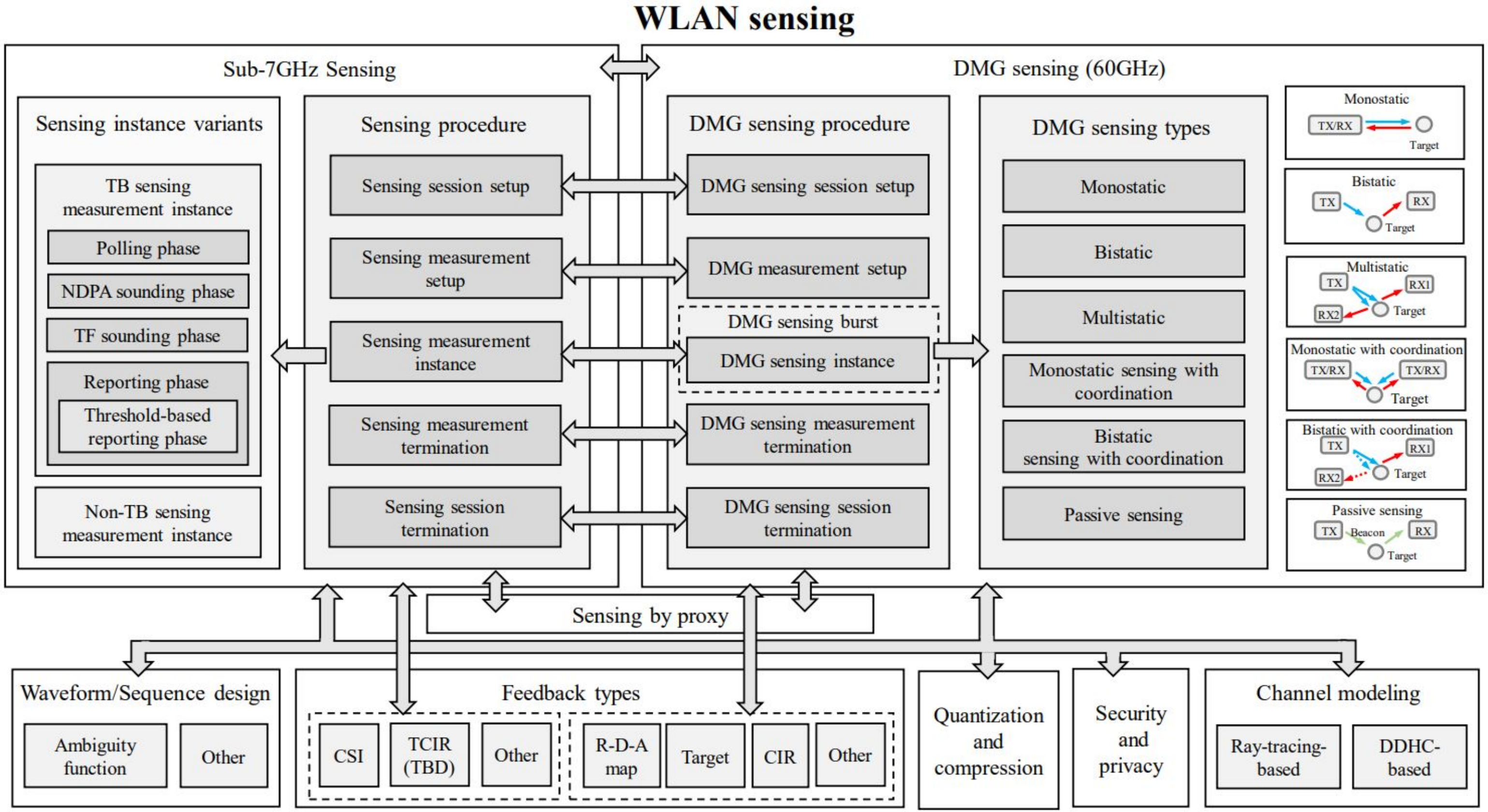
IEEE 802.11bf (contd)

- Sensing session (initiated by some STA)
  - Measurement setup (STAs agree on roles, attributes and reports): Setup ID
    - Measurement instance (transmit and receive NDPs): Measurement ID
  - Setup termination
- Measurement report sharing (optional - e.g., when CSI changes)
- Session termination
- AP coordinated: X-static
- Client sensing: Bi-static; multi-static enabled through proxy

IEEE 802.11bf (example)



Summary



Source: R. Du et al, "An Overview on IEEE 802.11bf: WLAN Sensing", arXiv, 2022.

WiFi Sensing (example)

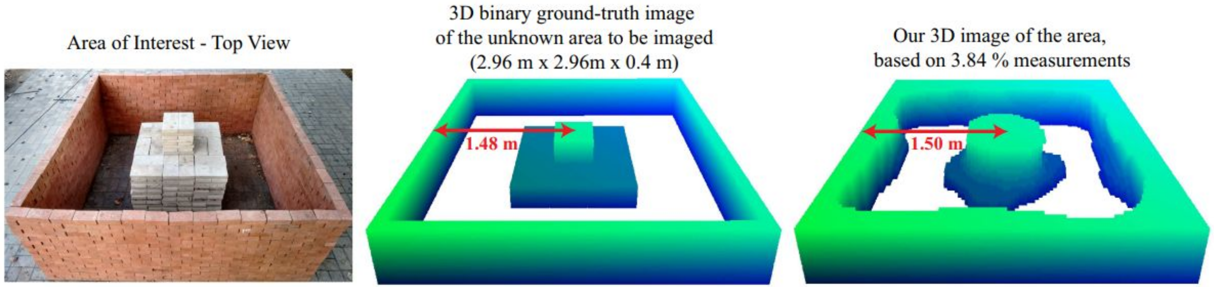


Figure 10: (left) The area of interest for the two-cube scenario, (middle) 3D binary ground-truth image of the unknown area to be imaged, which has the dimensions of 2.96 m $\times$ 2.96 m $\times$ 0.4 m, and (right) the reconstructed 3D binary image using our proposed framework.

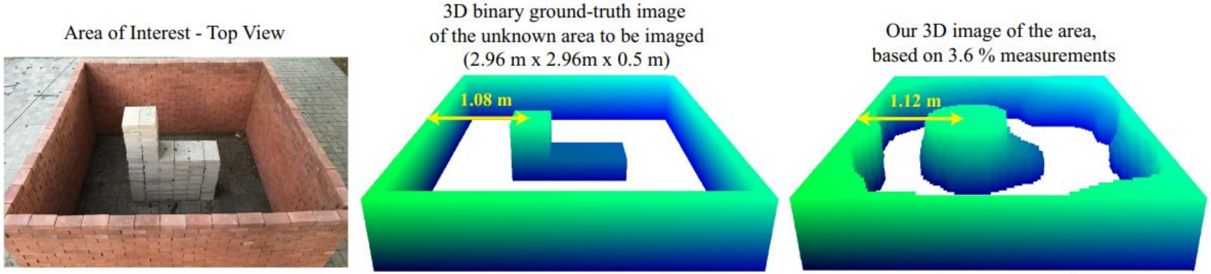


Figure 11: (left) The area of interest for the L-shape scenario, (middle) 3D binary ground-truth image of the unknown area to be imaged, which has the dimensions of 2.96 m $\times$ 2.96 m $\times$ 0.5 m, and (right) the reconstructed 3D binary image using our proposed framework.

Source: C. R. Karanam & Y. Mostofi, “3D Through-Wall Imaging with Unmanned Aerial Vehicles Using WiFi”, IEEE IPSN 2017.

5G/6G

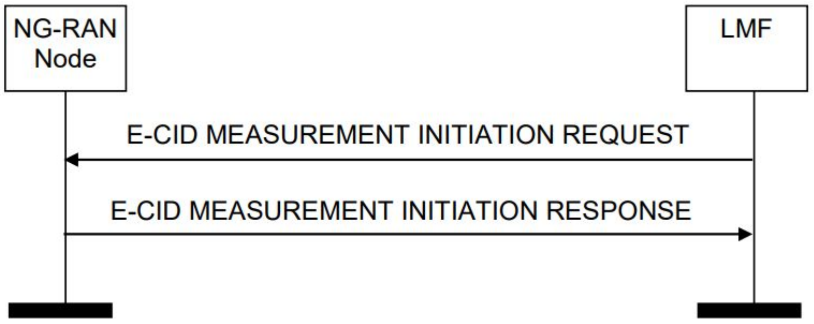
- GPS meets most needs; focus on V2X & GPS-denied areas
- 3GPP Rel 16 & 17: Positioning using AoA, TDoA, RTT, RSRP
- Location management function (LMF) in core central unit
- New protocol: NR positioning protocol A
- Legacy support: LMF to LTE positioning protocol (LPP)
- RB/Beam multiplexing between data and positioning
- Low correlation pilot sequences reused as radar pulses

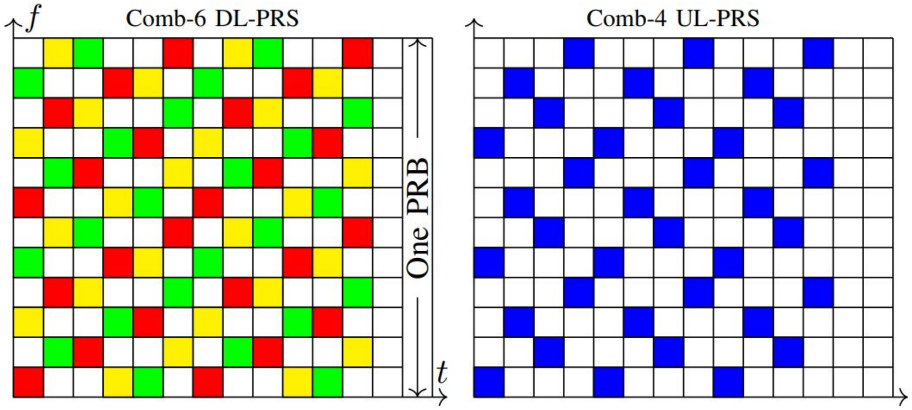
NR Positioning Protocol A (NRPPa)

- E-CID Measurement Initiation - Report - Termination
  - Similarly, TDOA/TRP Information Transfer
- Positioning: PRS (hi-BW) in DL, SRS (low-BW) in UL
- PRS: 24 to 276 RBs, repetition period: 4 to 10240 ms
  - RBs in comb pattern, QPSK, Gold sequence, beam sweep
- SRS: 1-12 symbols, ZC sequence
- Comb pattern: Orthogonal in shift, shift and allot to multiple BS, interference avoidance and suppression

Summary

Source: 3GPP Rel 16 document





Positioning service level	Absolute(A) or Relative(R) positioning	Accuracy (95 % confidence level)		Positioning service availability	Positioning service latency	Coverage, environment of use and UE velocity		
		Horizontal Accuracy	Vertical Accuracy (note 1)			5G positioning service area	5G enhanced positioning service area (note 2)	
							Outdoor and tunnels	Indoor
1	A	10 m	3 m	95 %	1 s	Indoor - up to 30 km/h Outdoor (rural and urban) up to 250 km/h	NA	Indoor - up to 30 km/h
2	A	3 m	3 m	99 %	1 s	Outdoor (rural and urban) up to 500 km/h for trains and up to 250 km/h for other vehicles	Outdoor (dense urban) up to 60 km/h Along roads up to 250 km/h and along railways up to 500 km/h	Indoor - up to 30 km/h
3	A	1 m	2 m	99 %	1 s	Outdoor (rural and urban) up to 500 km/h for trains and up to 250 km/h for other vehicles	Outdoor (dense urban) up to 60 km/h Along roads up to 250 km/h and along railways up to 500 km/h	Indoor - up to 30 km/h
4	A	1 m	2 m	99,9 %	15 ms	NA	NA	Indoor - up to 30 km/h
5	A	0,3 m	2 m	99 %	1 s	Outdoor (rural) up to 250 km/h	Outdoor (dense urban) up to 60 km/h Along roads and along railways up to 250 km/h	Indoor - up to 30 km/h
6	A	0,3 m	2 m	99,9 %	10 ms	NA	Outdoor (dense urban) up to 60 km/h	Indoor - up to 30 km/h
7	R	0,2 m	0,2 m	99 %	1 s	Indoor and outdoor (rural, urban, dense urban) up to 30 km/h Relative positioning is between two UEs within 10 m of each other or between one UE and 5G positioning nodes within 10 m of each other (note 3)		

Future

Waveforms

Joint & Distributed Algorithms

AI/ML

Opinions & Summary

Waveforms

- Need: Low PAPR, high spectral efficiency, multiple access
- OTFS
  a. High mobility support
  b. Embedded Doppler processing
  c. Multiple access similar to OFDM
- Single carrier
  a. Improved capacity
  b. Suitable for CRAN, distributed ICaS
- MC-CDMA - NOMA
  a. Occupy full bandwidth
  b. Suitable for less dense rural areas
  c. Simple multiplexing

Academic -- -- Implementation

Joint & Distributed Algorithms

Academic -- -- Implementation

- Joint: Same signal for data and sensing; e.g., cyclic prefix
- Distributed:
  - CRAN: centralized data fusion, position broadcasting
  - CoMP, coordinated MIMO, interference avoidance/alignment
- RIS: Holographic MIMO
  - Modify channel properties to enhance performance
- Cognitive ICaS: Dynamic spectrum sharing and allocation
- Compressed sensing: Exploiting spatial geometry sparsity

AI/ML

- PCA, feature selection/identification for detection
- Deep learning: device non-linearities, channel variations, temporal and spatial traits of propagation environment
    - Learn model from *a lot* of data (offline)
    - Continuously update model (online)
- Neural networks for system inversion/deconvolution
- RF fingerprinting to identify/predict devices and track
- Learn waveforms, schedules, resource allocation, precoders
- Distributed/federated learning for multistatic sensing
- Data driven sensing: Learn from past data

Academic -- -- Implementation

Summary & Opinions

- Immediate need: Waveforms and scheduling algos
- Future technologies to improve capacity and accuracy
  - ICaS without any multiplexing
- OEM intelligence: Fusion algorithms and ML models
- Ongoing: 802.11bf, EU-OTFS-RADCOM, Hexa-X
- 3GPP playing catch-up
- Privacy concerns
- THz: hardware, optics, range, 3D-imaging

Thank you

Questions