Radio Localization and Sensing: the Path from 5G to 6G

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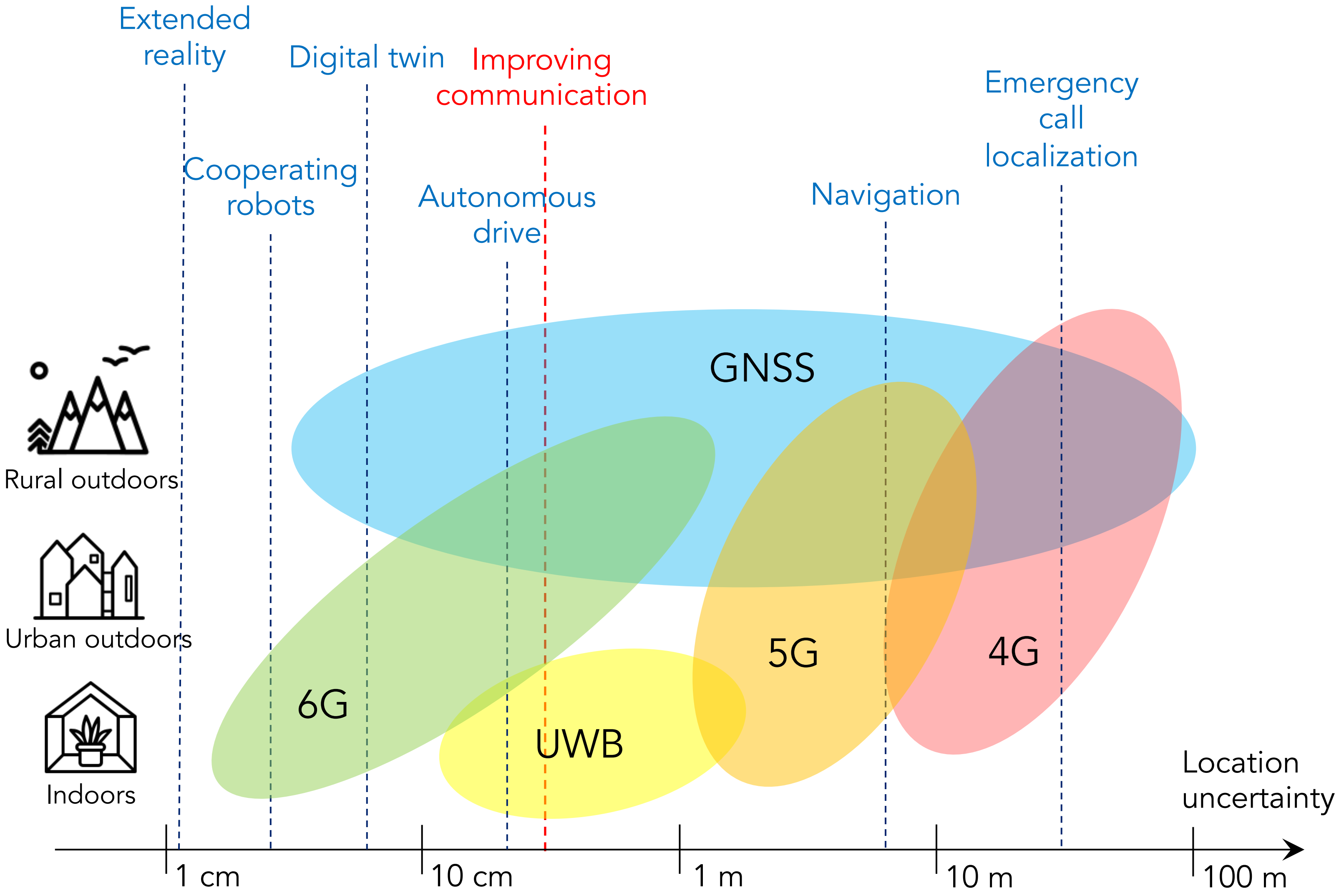
Why do we want 6G localization and sensing?

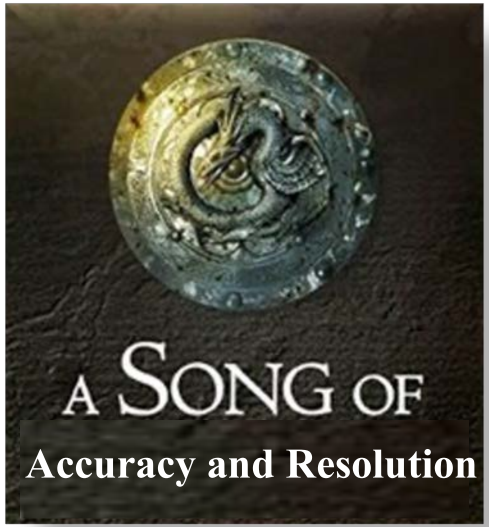


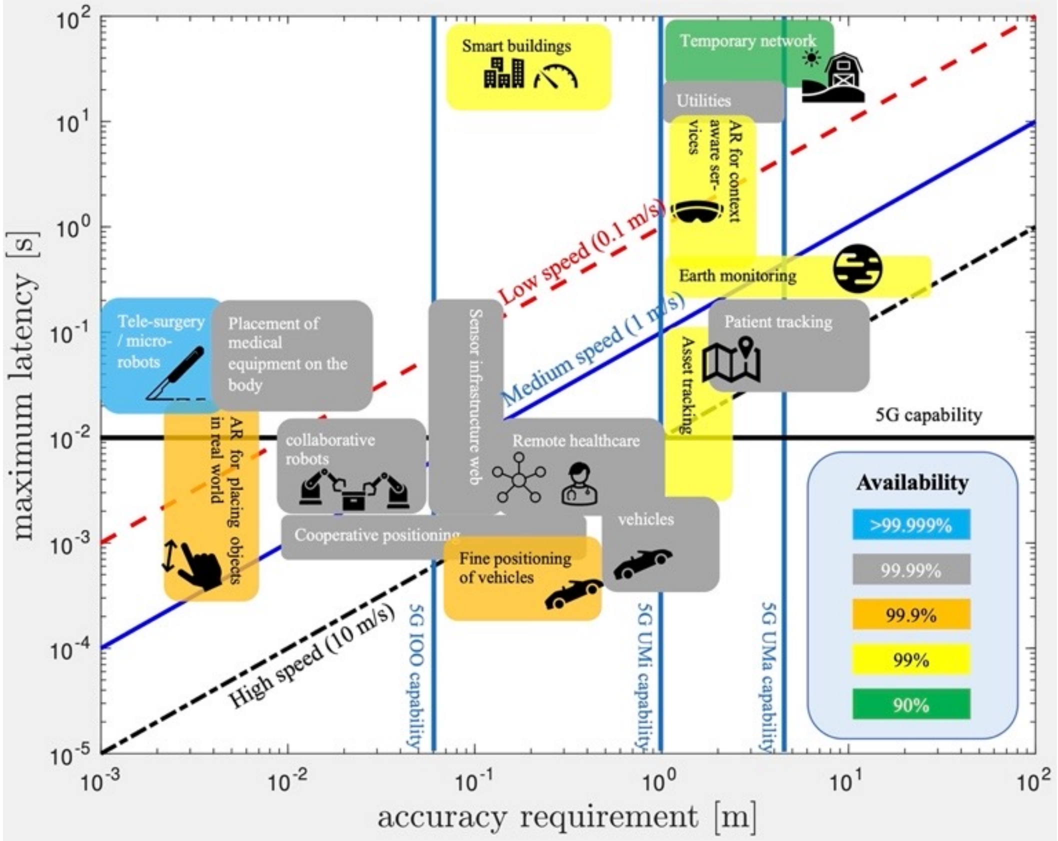
Wymeersch, H. and Seco-Granados, G., 2022. Radio localization and sensing—Part I: Fundamentals. *IEEE Communications Letters*, *26*(12), pp.2816-2820.

Wymeersch, H. and Seco-Granados, G., 2022. Radio Localization and Sensing—Part II: State-of-the-Art and Challenges. *IEEE Communications Letters*, *26*(12), pp.2821-2825.

How to measure performance?

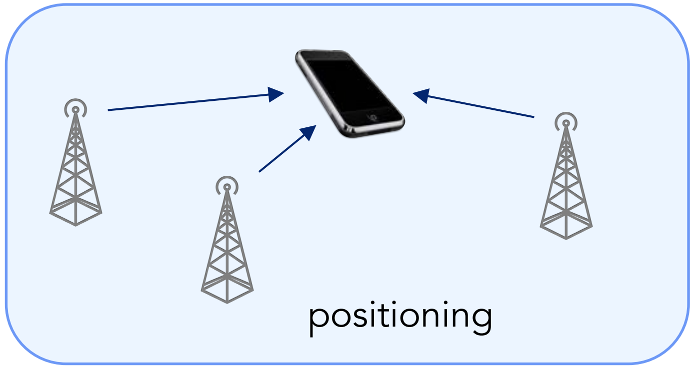
- **Positioning/localization:** estimate location of a connected device
- **Accuracy (m):** error in location (XY, XYZ) that can be attained in a statistical sense (e.g., 90% of the time/space, or RMSE).
- **Resolution:** ability to resolve multipath in delay, angle, Doppler, or position.
- **Latency (s):** time between positioning request and availability of the position estimate. Includes also the over-the-air-latency.
- **Update rate (Hz):** frequency of the position estimates. Limited by the latency.
- **Mobility (m/s):** typical speed of objects

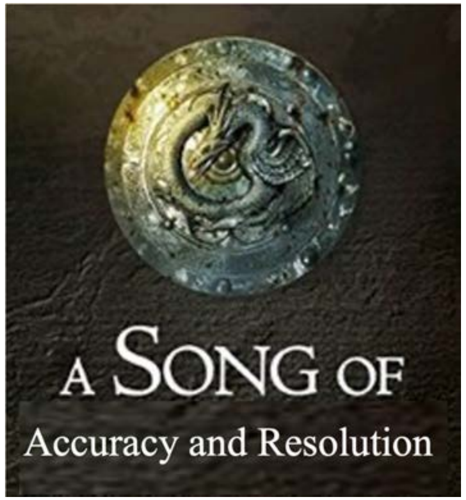


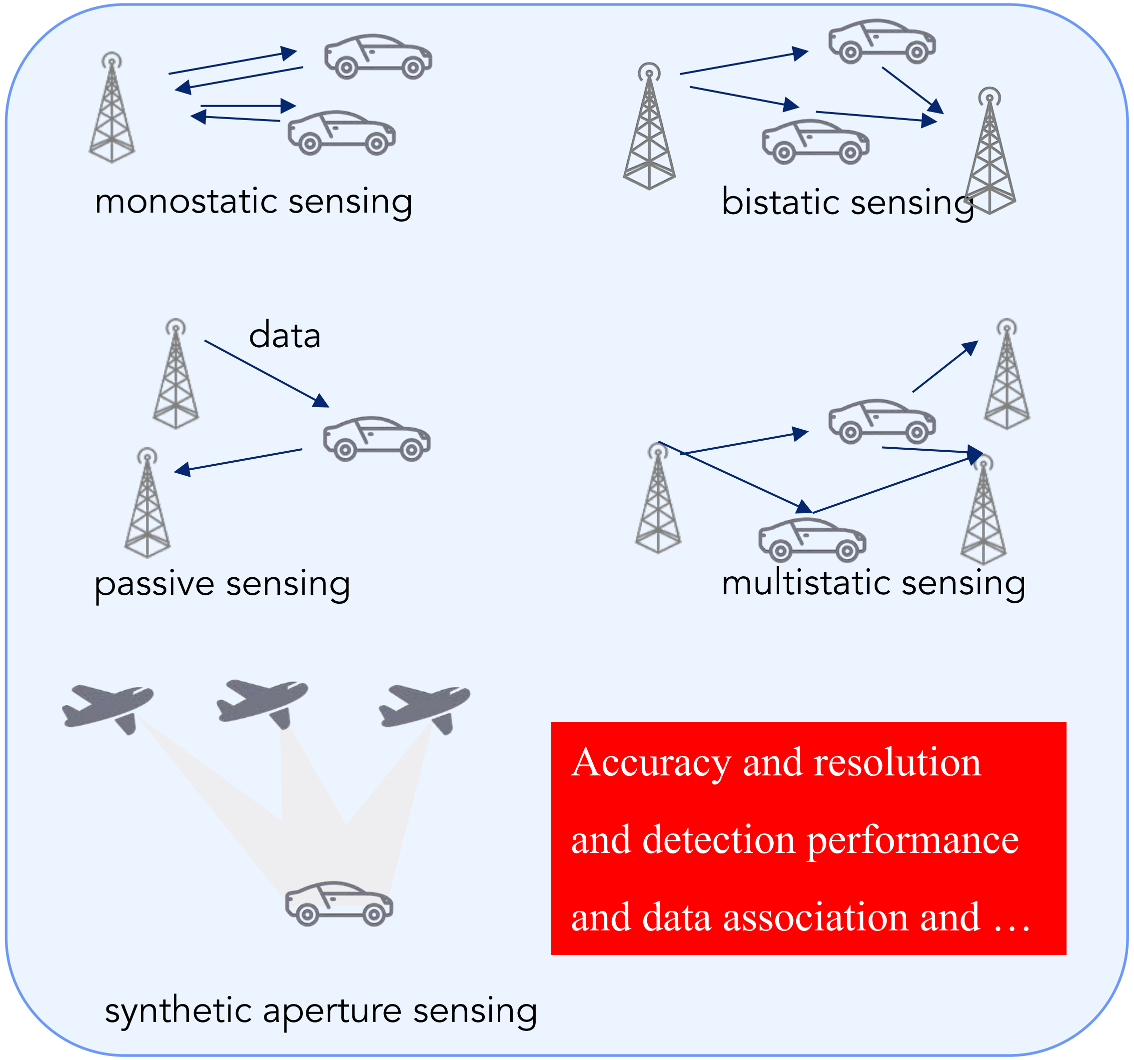


Behravan A, Yajnanarayana V, Keskin MF, Chen H, Shrestha D, Abrudan TE, Svensson T, Schindhelm K, Wolfgang A, Lindberg S, Wymeersch H. "Positioning and Sensing in 6G: Gaps, Challenges, and Opportunities," IEEE Vehicular Technology Magazine, 2023.

From positioning to radar-like sensing

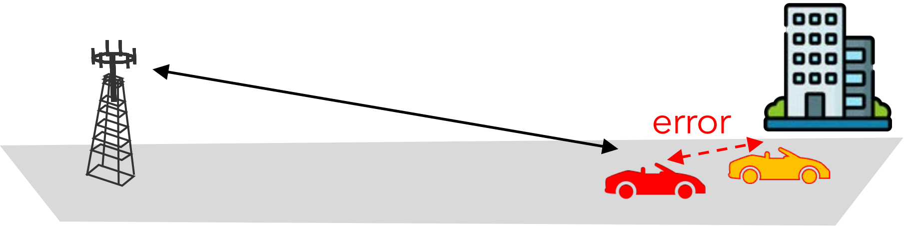






Accuracy and resolution
and detection performance
and data association and …

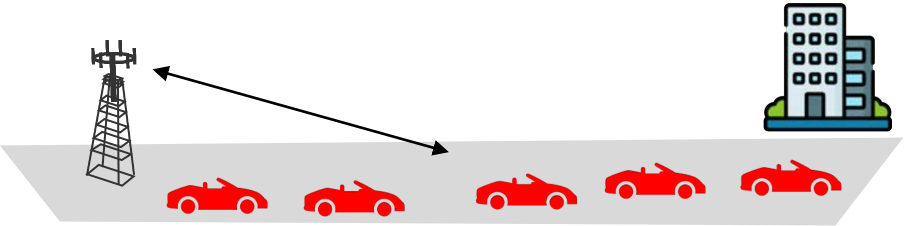
Accuracy



- Localization / sensing error $\boldsymbol{e} = \boldsymbol{x} - \hat{\boldsymbol{x}}$
- Accuracy, based on statistics of $\boldsymbol{e}$
  - 90% (or 99%) percentile of the norm of $\boldsymbol{e}$
  - Root mean squared error (RMSE) $\sqrt{\mathbb{E}\{\|\boldsymbol{e}\|^2\}}$
- Lower bound on RMSE: Cramér-Rao bound (CRB)
  - Unknown $\boldsymbol{\kappa} = [\boldsymbol{\eta}^\top, \boldsymbol{\xi}^\top]^\top$
  - Observations $\boldsymbol{y}_{n,k} = \boldsymbol{\mu}_{n,k}(\boldsymbol{\kappa}) + \boldsymbol{n}_{n,k}$
  - Fisher information matrix (FIM) of $\boldsymbol{\kappa}$: $\boldsymbol{J}(\boldsymbol{\kappa}) = 2/N_0 \sum_{n,k} \Re\Big\{ \Big(\frac{\partial \boldsymbol{\mu}_{n,k}}{\partial \boldsymbol{\kappa}}\Big)^{\mathsf{H}} \frac{\partial \boldsymbol{\mu}_{n,k}}{\partial \boldsymbol{\kappa}} \Big\}$
  - CRB of parameters of interest $\boldsymbol{\eta}$ (under certain conditions)
    $$\sqrt{\mathbb{E}\{\|\boldsymbol{\eta} - \hat{\boldsymbol{\eta}}\|^2\}} \geq \sqrt{\mathrm{trace}[\boldsymbol{J}^{-1}(\boldsymbol{\kappa})]_{1:d_{\boldsymbol{\eta}},1:d_{\boldsymbol{\eta}}}}$$
  - Position error bound (PEB) is the CRB of the location
  - Useful as lower bound for estimators and to design systems (BS placement, waveform)
- Accuracy is only meaningful when objects can be resolved

Resolution

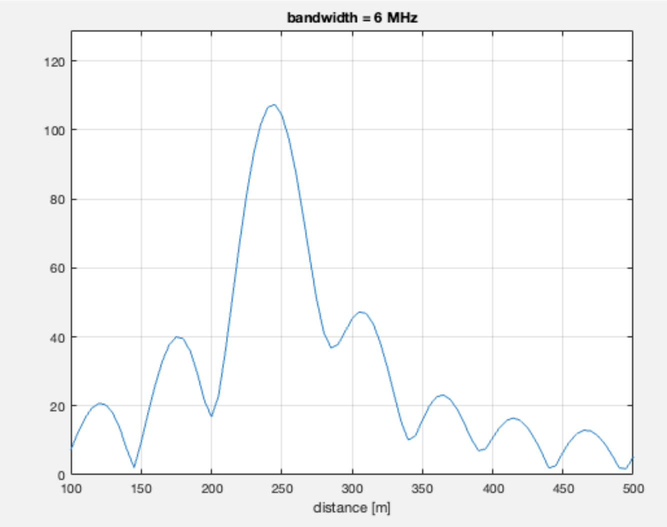
- Example:
  - Wideband: objects are separated
  - Narrowband: objects looks as merged into one
- Resolution: ability to resolve paths / objects
  - Delay / range resolution: $|\tau_l - \tau_{l'}| > 1/W$
  - Angle resolution: $|\theta_l - \theta_{l'}| > 2/N_{\text{ant}}$
  - Doppler resolution: $|\nu_l - \nu_{l'}| > 1/(KT_s)$
- Resolution thresholds can be improved with super-resolution methods at high SNR.

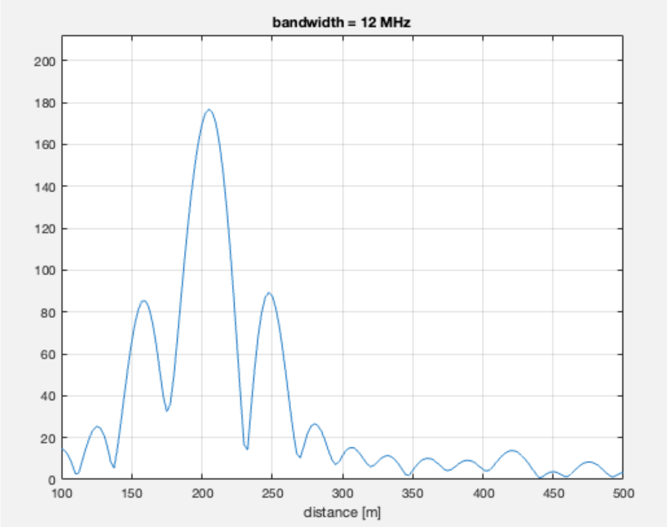


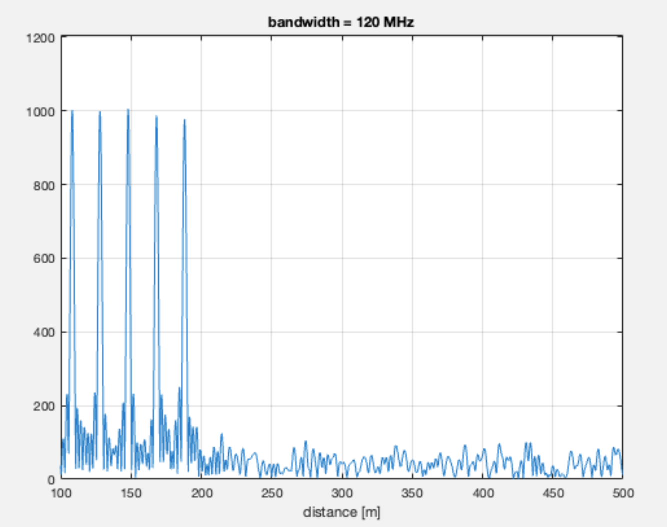
All dimensions have common form

$$y_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} + n_n$$

$$\omega_l: \quad 2\pi\tau_l\Delta_f, \quad \pi\sin\theta_l, \quad 2\pi\nu_l T_s$$







Outline

- Foundations of radio localization and sensing
- Localization in 5G: practice and potentials
- Integrated communication and sensing/localization towards 6G
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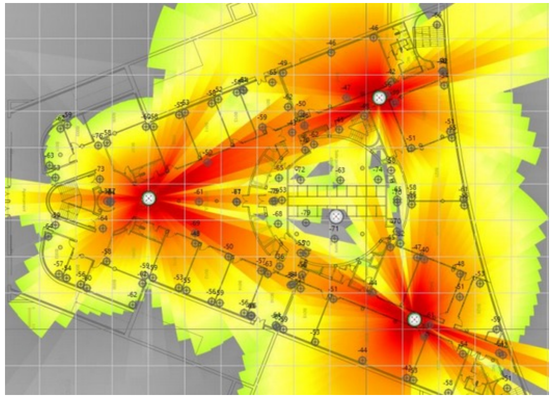
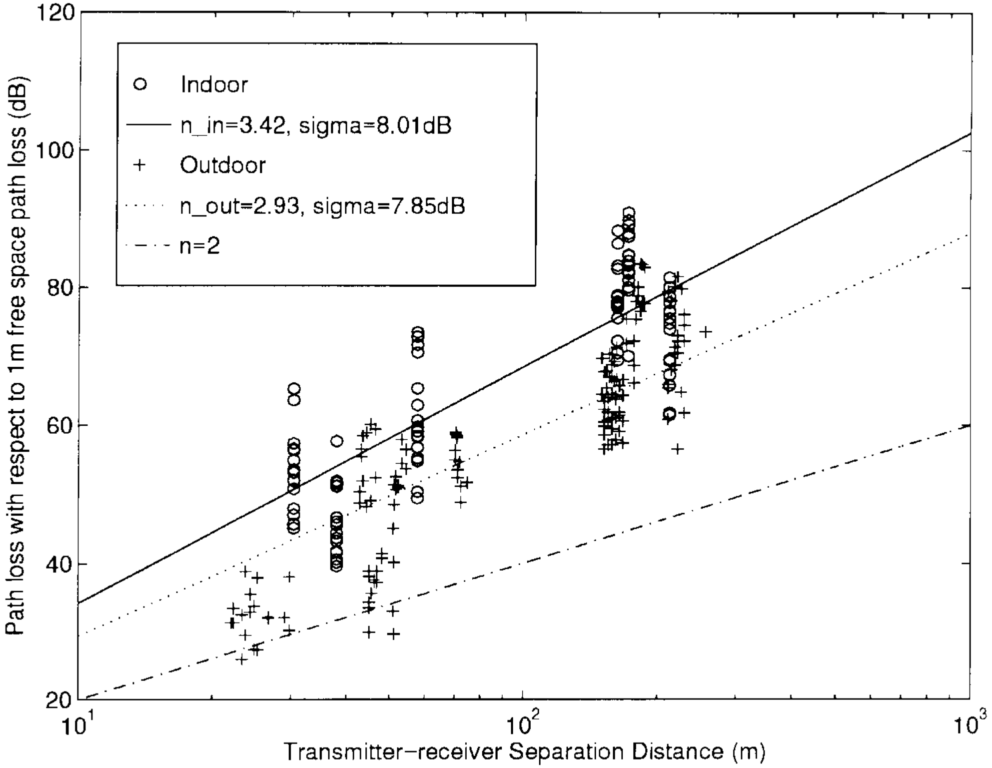
Signal strength

- Principle
  - Path loss equation $P_r[\mathrm{dBm}] = P_t[\mathrm{dBm}] + K[\mathrm{dB}] - 10\gamma \log_{10} \frac{d}{d_0}$
  - Learn parameters from data
  - Map received power to distance
- Challenges
  - Not one-to-one mapping
  - Many meters distance uncertainty
  - More common with fingerprinting



http://air-go.es/technology/fingerprinting/



Durgin, Greg, Theodore S. Rappaport, and Hao Xu. "Measurements and models for radio path loss and penetration loss in and around homes and trees at 5.85 GHz." IEEE Transactions on Communications 46.11 (1998): 1484-1496.

Time

- We consider OFDM pilot transmission
- Transmitted signal over N subcarriers

$$\mathbf{s} = [s_0, \ldots, s_{N-1}]^\top$$

- Received signal after unknown delay, in receiver frame of reference

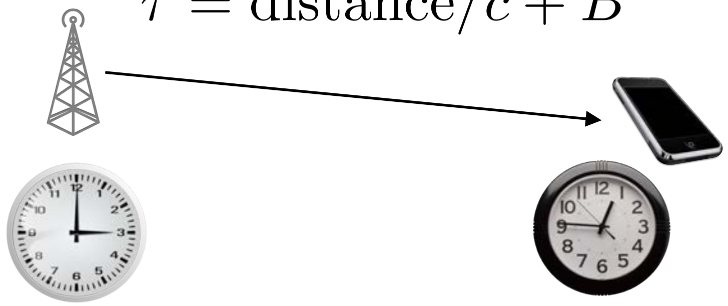
$$r_n = \alpha s_n \exp\left(-\jmath 2\pi n \tau / (N T_s)\right)$$

- Vectorize

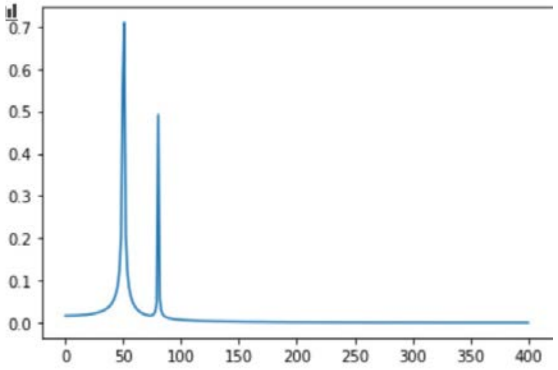
$$\mathbf{r} = \alpha \mathbf{s} \odot \mathbf{a}(\tau)$$

$$[\mathbf{a}(\tau)]_n = \exp\left(-\jmath 2\pi n \tau / (N T_s)\right)$$

$$\tau = \text{distance}/c + B$$

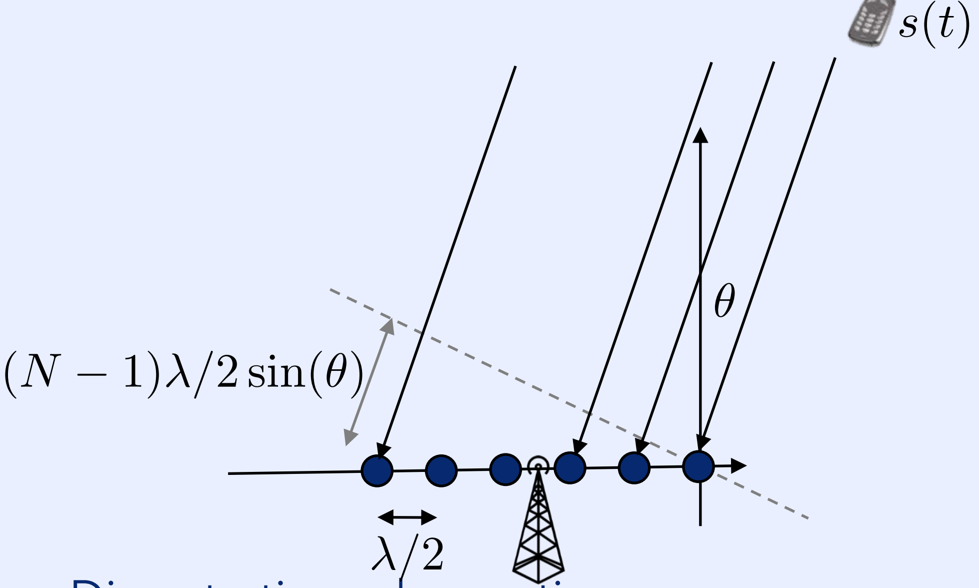


- Delay relates to time-of-flight and clock bias
- Estimation can be based on FFT
- Resolution depends on bandwidth



Angle of arrival (AOA) and angle of departure (AOD)

- **AOA Operation:** narrowband signal, plane wavefronts



- Discrete time observation

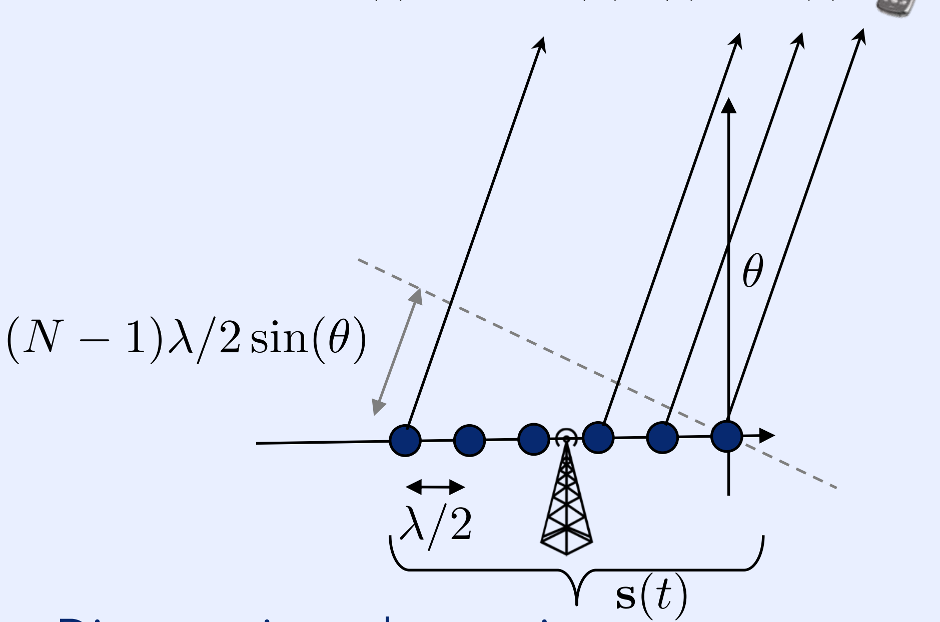
$$\mathbf{r} = \alpha\mathbf{a}(\theta) + \mathbf{n}$$

$$[\mathbf{a}(\theta)]_n = \exp(-\jmath\pi n \sin(\theta))$$

- Estimation with, e.g., FFT
- Resolution depends on aperture

- **AOD Operation:** narrowband signal, plane wavefronts

$$r(t) = \alpha\mathbf{a}^\top(\theta)\mathbf{s}(t) + n(t)$$



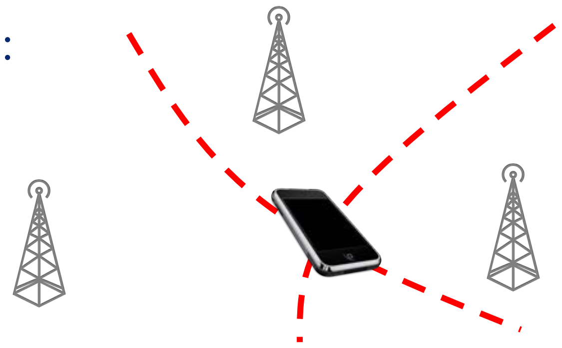
- Discrete time observation

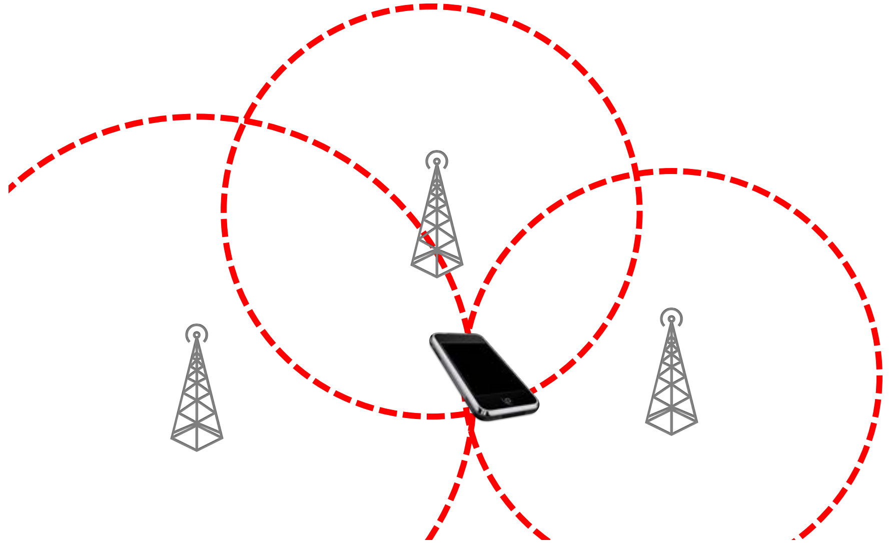
$$r_t = \alpha\mathbf{a}^\top(\theta)\mathbf{s}_t + n_t$$

- Estimation with, e.g., OMP
- Resolution depends on aperture

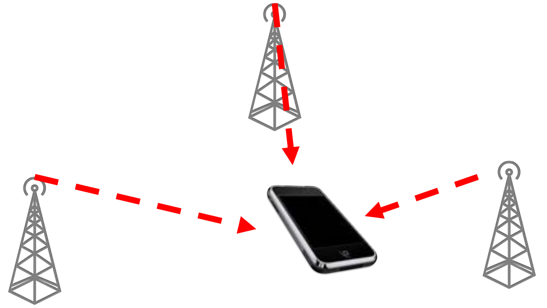
From measurements to positions

- Delay-based positioning:

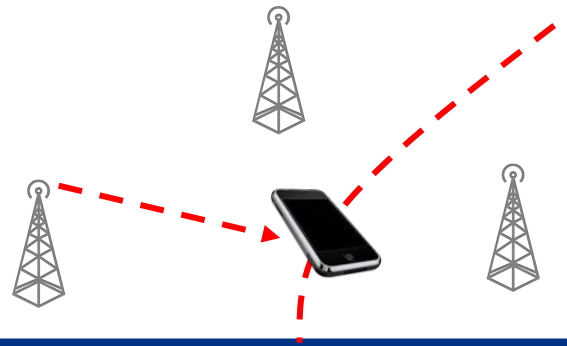




- Angle-based positioning:



- Combinations:



$$\mathbf{y} = \mathbf{f}(\mathbf{x}) + \mathbf{n}$$

$$\hat{\mathbf{x}}(\mathbf{y}) = \arg\min_{\mathbf{x}} \|\mathbf{y} - \mathbf{f}(\mathbf{x})\|^2$$

Typically non-convex

From positioning to sensing: monostatic radar

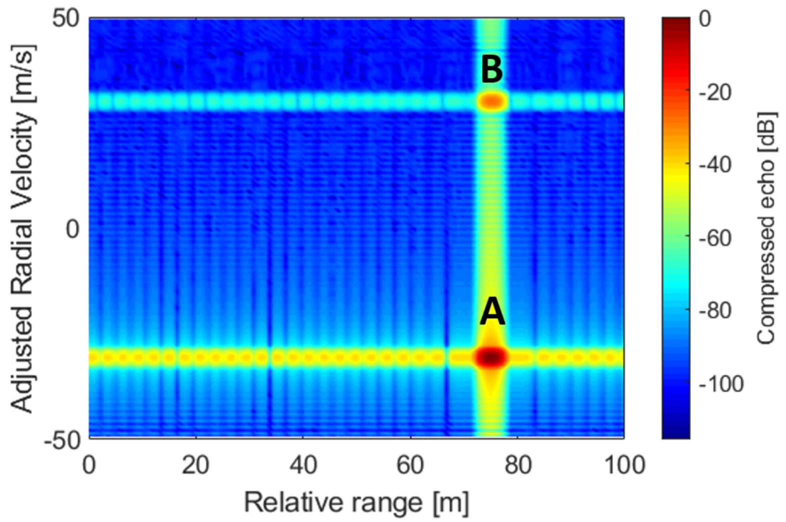
Carvajal, G., Keskin, F., Aydogdu, C. et al (2020). Comparison of Automotive FMCW and OFDM Radar Under Interference. IEEE National Radar Conference - Proceedings, 2020-September.

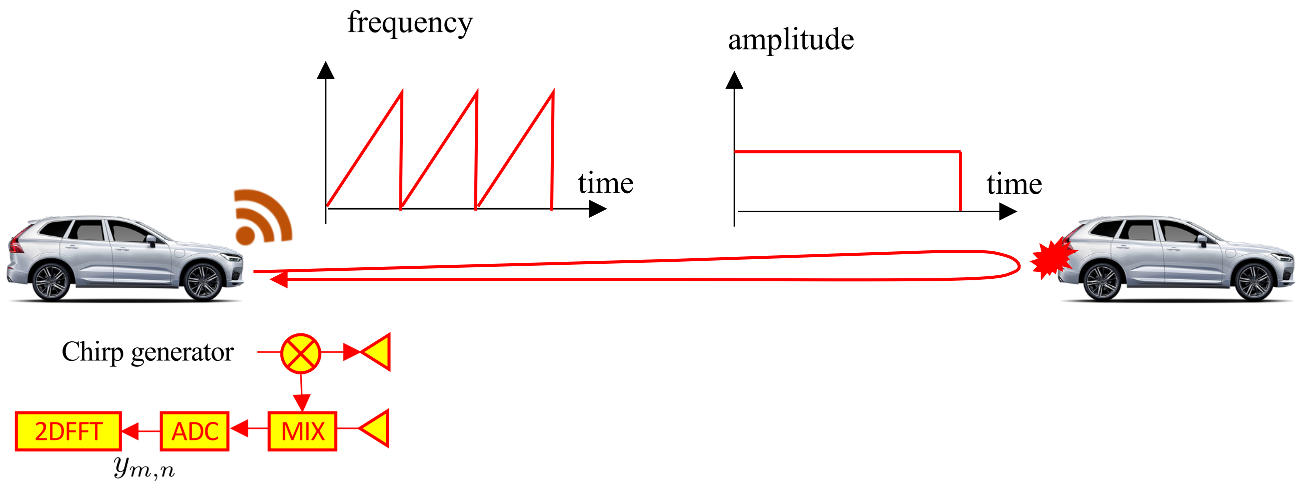
Sturm, C. and Wiesbeck, W., 2011. Waveform design and signal processing aspects for fusion of wireless communications and radar sensing. Proceedings of the IEEE, 99(7), pp.1236-1259.

- Sample signal across time and frequency

$$r_k[nT_s] = \gamma \exp\left(-\jmath 2\pi n T_s \alpha \tau\right) \exp\left(\jmath 2\pi f_c \nu k T\right) + z_k[nT_s]$$

- Peaks in 2D FFT provide range/Doppler of targets





- Detection of multiple targets (e.g., CFAR)
- Can also be extended to the antenna domain to obtain angles

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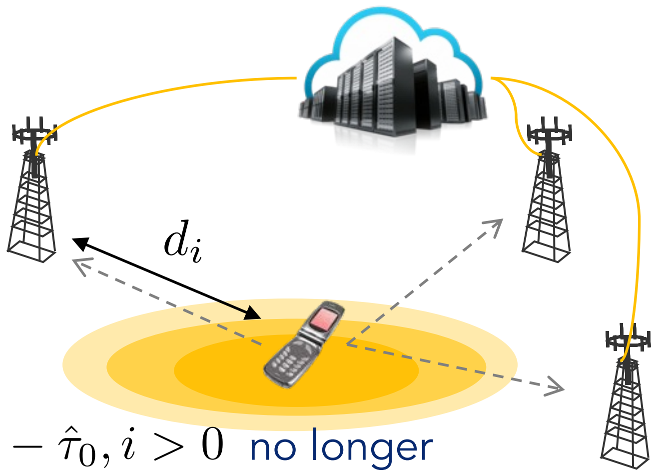
Typical 5G approach: time-difference-of-arrival (TDOA)

Operation

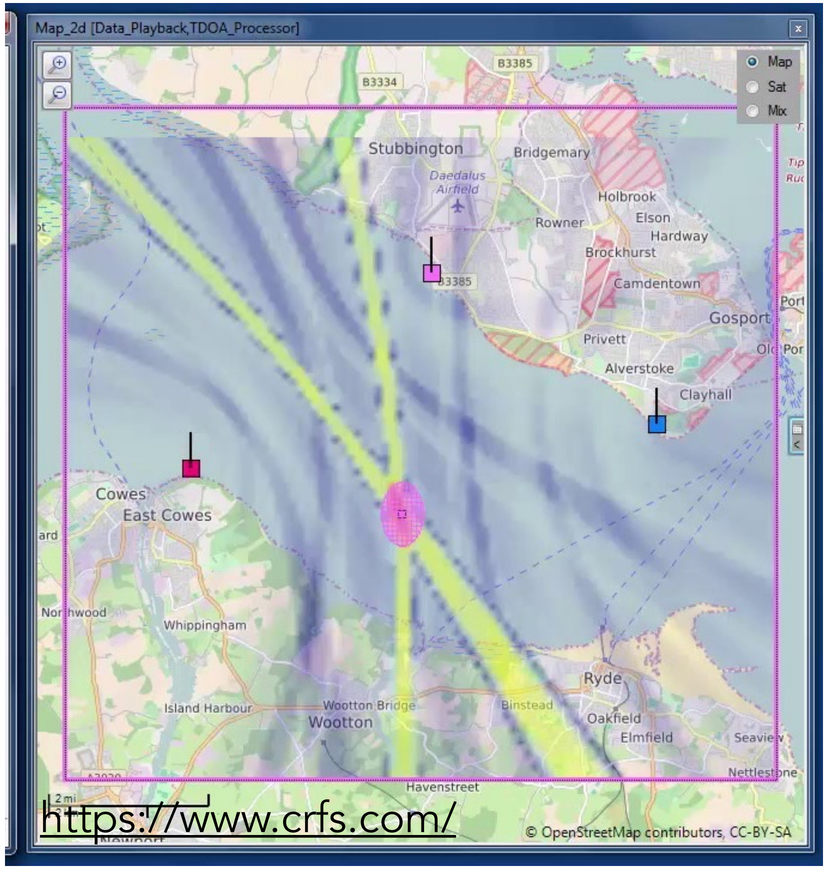


- Estimate $\hat{\tau}_i = d_i/c + B + n_i$
- Differential measurement $y_i = \hat{\tau}_i - \hat{\tau}_0, i > 0$ no longer depends on bias *B*
- Find intersection of several hyperbola

Performance limitation

- Main limitation: resolution (= bandwidth)
- Also: base station placement, LOS

Many enhancements in 3GPP R16, 17, 18

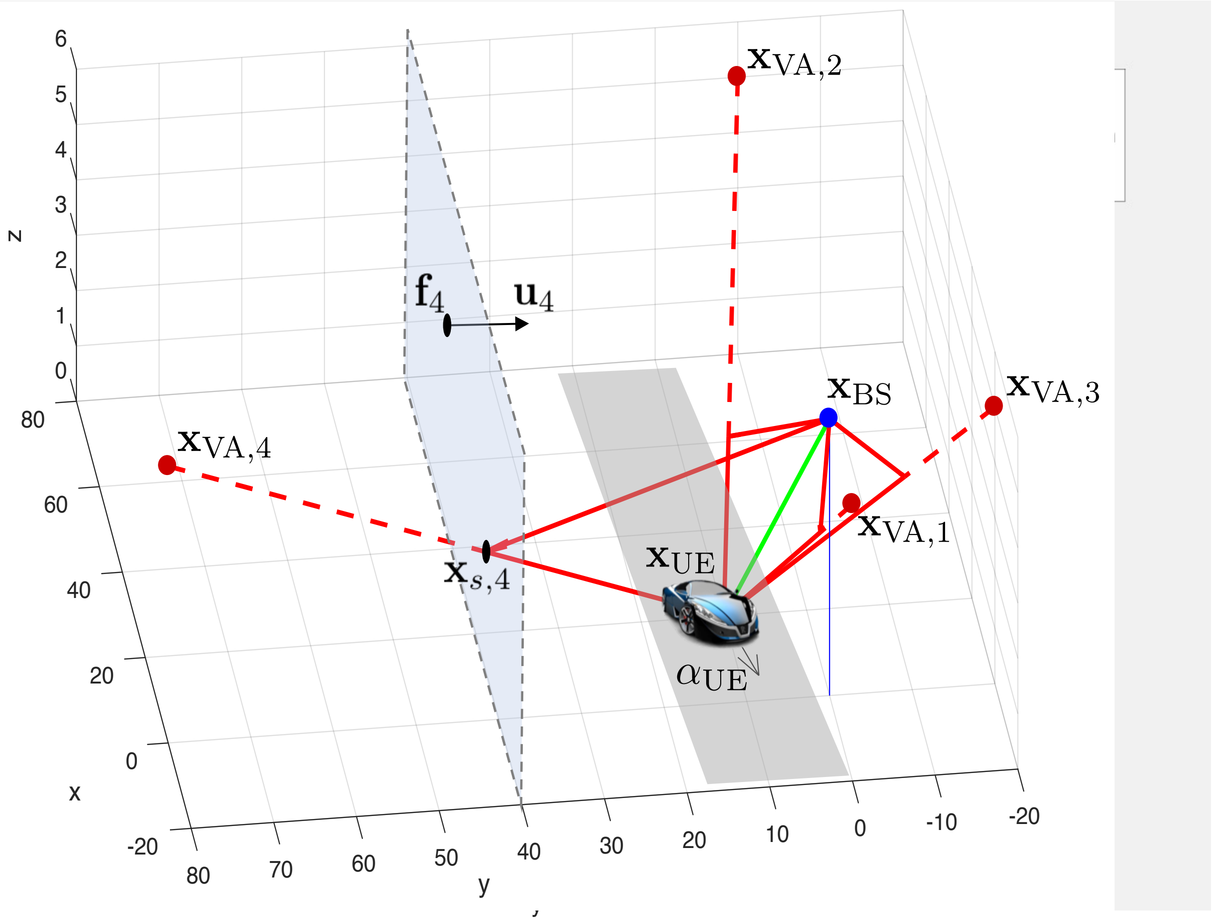


https://www.crfs.com/

Dwivedi S, Shreevastav R, Munier F, Nygren J, Siomina I, Lyazidi Y, Shrestha D, Lindmark G, Ernström P, Stare E, Razavi SM. "Positioning in 5G networks", IEEE Communications Magazine. 2021 Dec 30;59(11):38-44.

Potentials 1/3: radio SLAM

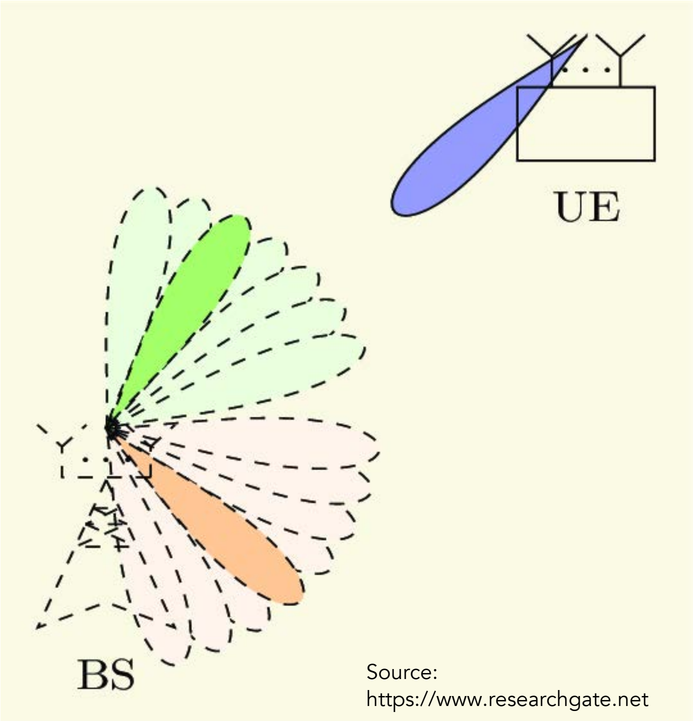
- **Conventional thinking:** multipath is foe
- **Insight:** With angle measurements at UE and BS:
  - Each multipath component has 3 geometric unknowns, up to 5 observables
  - So multipath can be our friend!
- **Outcomes:**
  - Multipath can be exploited to perform single-BS UE positioning, synchronization, and environment mapping → *Radio-SLAM*
  - Even possible without LOS path.
  - Synchronization problem solved "by nature".
- **Validation:**
  - https://www.youtube.com/watch?v=wAV0_uMpSDo
  - Collaboration with Lund Univ. QAMCOM, Ericsson, Veoneer, CEVT

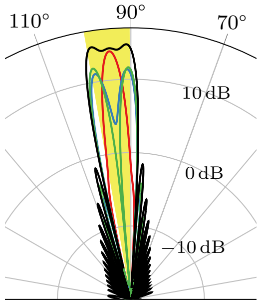


Ge, Y., Kaltiokallio, O., Kim, H., Jiang, F., Talvitie, J., Valkama, M., Svensson, L., Kim, S. and Wymeersch, H., 2022. A computationally efficient EK-PMBM filter for bistatic mmWave radio SLAM. IEEE Journal on Selected Areas in Communications, 40(7), pp.2179-2192.
Ge, Y., Khosravi, H., Jiang, F., Chen, H., Lindberg, S., Hammarberg, P., Kim, H., Brunnegård, O., Eriksson, O., Olsson, B.E. and Tufvesson, F., 2023. Experimental Validation of Single BS 5G mmWave Positioning and Mapping for Intelligent Transport. arXiv preprint arXiv:2303.11995.

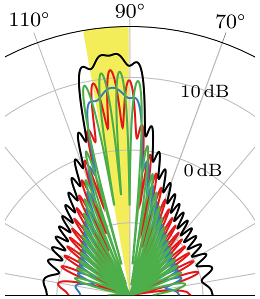
Potentials 2/3: per-user signal optimization

- **Conventional thinking:** PRS combined with directional beams. Are these optimal? No, since energy is wasted in certain directions.
- **Insight:**
  - Under a priori UE information, much better signals can be determined (in space, time, frequency)
  - Relation to radar sum- and difference beams, with power allocation
- **Outcomes:**
  - Optimized precoders, combiners can significantly improve positioning performance.
- **Validation:**
  - See D3.3 https://hexa-x.eu/deliverables/
  - Collaboration QAMCOM
  - Sub-degree accuracy possible using tailored beams with 10 degrees beamwidth





(c) AoA-optimal precoders (Problem 3). The rank of **X** is 3.



(b) AoD-optimal precoders (Problem 2). The rank of **X** is 2.

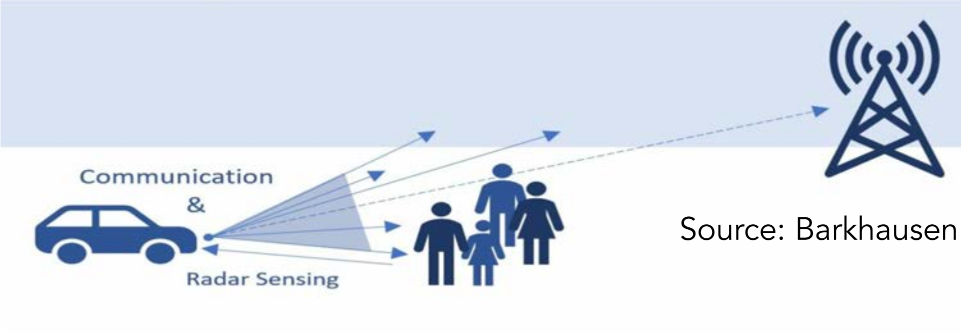
N. Garcia, H. Wymeersch, D. Slock, ”Optimal Precoders for Tracking the AoD and AoA of a mmWave Path”, in IEEE Transactions on Signal Processing, 2018.

A. Kakkavas, H. Wymeersch, G. Seco-Granados, M. H. Castañeda García, R. A. Stirling-Gallacher, and J. A. Nossek, "Power Allocation and Parameter Estimation for Multipath-based 5G Positioning", IEEE Transactions on Wireless Communications, 2021.

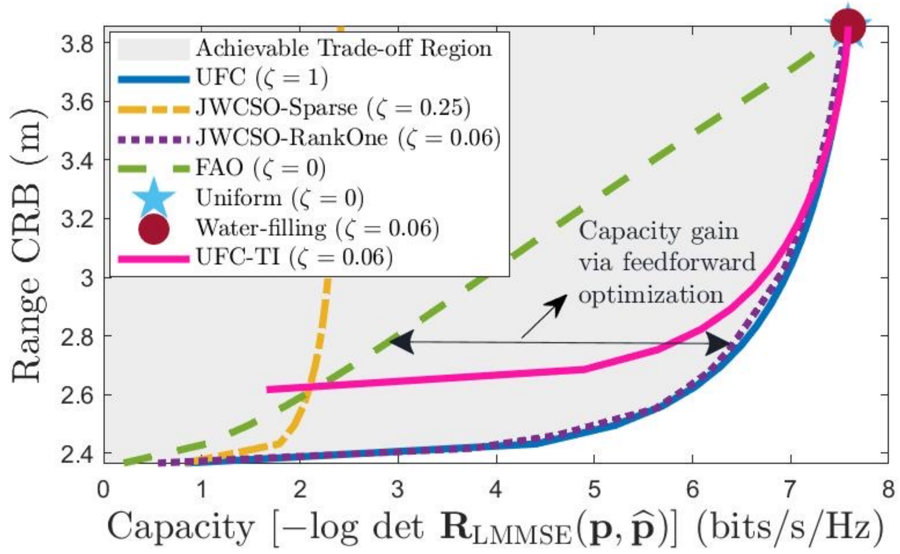
Musa Furkan Keskin, Fan Jiang, Florent Munier, Gonzalo Seco-Granados, Henk Wymeersch, "Optimal Spatial Signal Design for mmWave Positioning under Imperfect Synchronization", IEEE Transactions on Vehicular Technology, 2022,

Potentials 3/3: sensing

- **Conventional thinking:** full duplex transmission only for communication gains. Hardware impairments degrade performance
- **Insight:**
  - At high frequencies, where large bandwidths and large arrays are available, backscattered signals can reveal range and angle to targets. Similar to monostatic radar.
  - Hardware impairments in monostatic sensing can be related to targets.
- **Outcome:**
  - Communication waveform can be optimized (time, frequency, space) to trade-off communication and radar performance.
  - Impairments such as inter-carrier interference, phase noise can be exploited in monostatic sensing.
- **Validation:**
  - Ongoing project with Halmstad University, Magna, Volvo Cars
  - Stay tuned …



Source: Barkhausen Insittute



M. F. Keskin, V. Koivunen, and H. Wymeersch, "Limited Feedforward Waveform Design for OFDM Dual-Functional Radar-Communications," IEEE Transactions on Signal Processing, vol. 69, pp. 2955–2970, 2021.
Keskin, M.F., Wymeersch, H. and Koivunen, V., 2023. Monostatic sensing with OFDM under phase noise: From mitigation to exploitation. IEEE Transactions on Signal Processing.

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6G from a sensing and localization perspective

1. Variety of carrier frequencies (< 6, 7-10 GHz, 28, 140 GHz)
2. Large aggregate bandwidths (above 1 GHz)
3. Large number of antennas (3D orientation estimation)
4. Sidelinks (relative, cooperative positioning)
5. Distributed cell-free massive MIMO with phase coherence
6. Integration of sensing, localization, and communications
7. Data-driven solutions using AI/ML
8. Shaping the environment with RIS
9. Sky segment (UAV, LEO) complements terrestrial base stations

Main challenges

- Hardware impairments, much more severe than for communication
- Extreme performance requires extreme calibration

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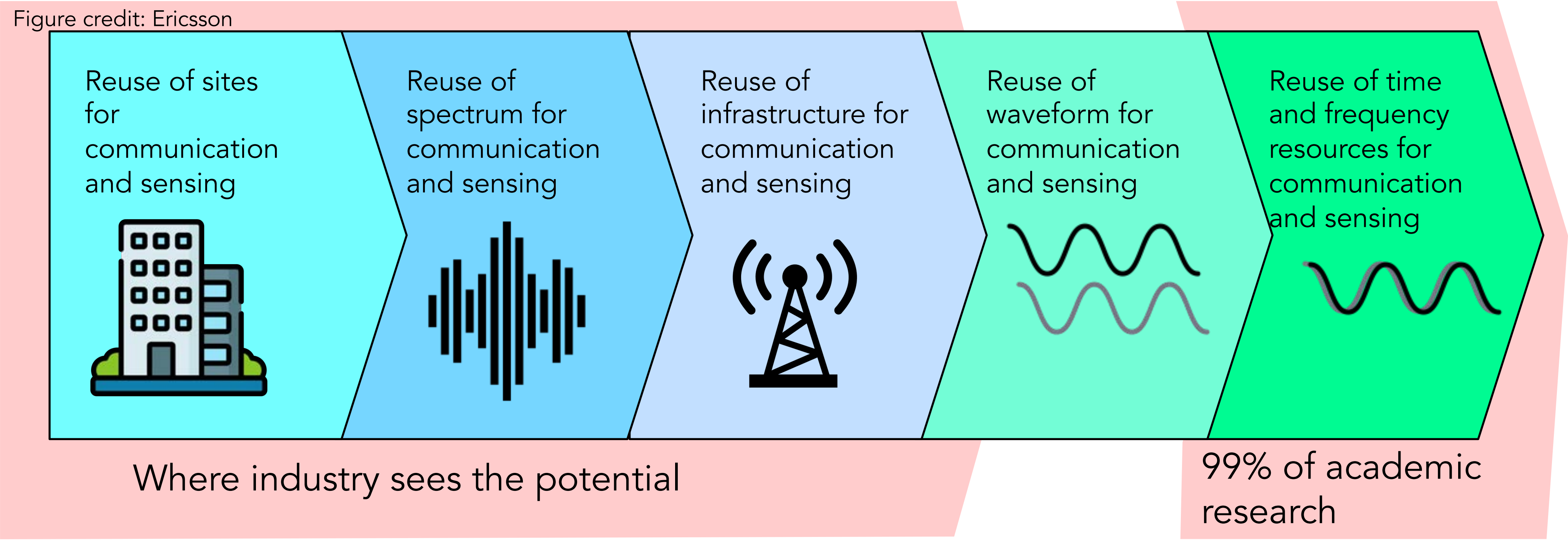
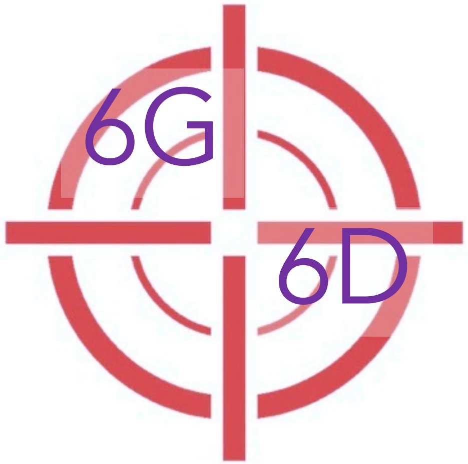
Integration of communication and sensing – ISAC, JCAS, DFRC,…



Dedicated positioning/sensing anchors (location reference)?
Hardware-friendly sensing waveform (e.g., FMCW, DFTS-OFDM) ?
Dedicated sensing, positioning pilots?
Trade-off or synergy between sensing and communications?
Harmonious operation in FR1, FR2, FR3?
Applications: radar-like and non-radar like sensing, improving communication

Henk Wymeersch, Athanasios Stavridis (EAB), Kim Schindhelm , Hui Chen, Hao Guo, Musa Furkan Keskin, Simon Lindberg, José Miguel Mateos-Ramos, Mohammad Hossein Moghaddam, Mohammad Ali Nazari, Indika Perera, Alejandro Ramirez, Rafaela Schroeder, Tommy Svensson, Andreas Wolfgang, Vijaya Yajnanarayana, "Final models and measurements for localisation and sensing," Hexa-X project Deliverable D3.3, 2023. [Online]. Available: https://hexa-x.eu/deliverables

6G from a sensing and localization perspective



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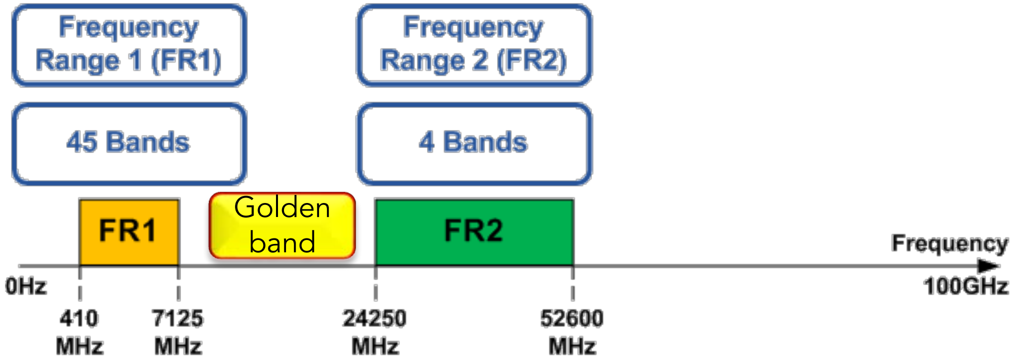
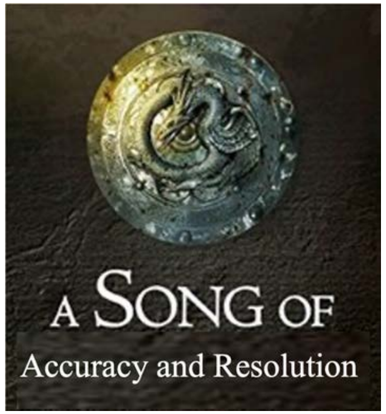
RISE-6G Hexa-X REINDEER
LOCUS ARIADNE
TIMES THz INDUSTRIAL MESH NETWORKS IN SMART SENSING & PROPAGATION ENVIRONMENTS
HEXA-X-II
ISLANDS MSCA DOCTORAL NETWORK

Will 6G be all about sub-THz? Probably not

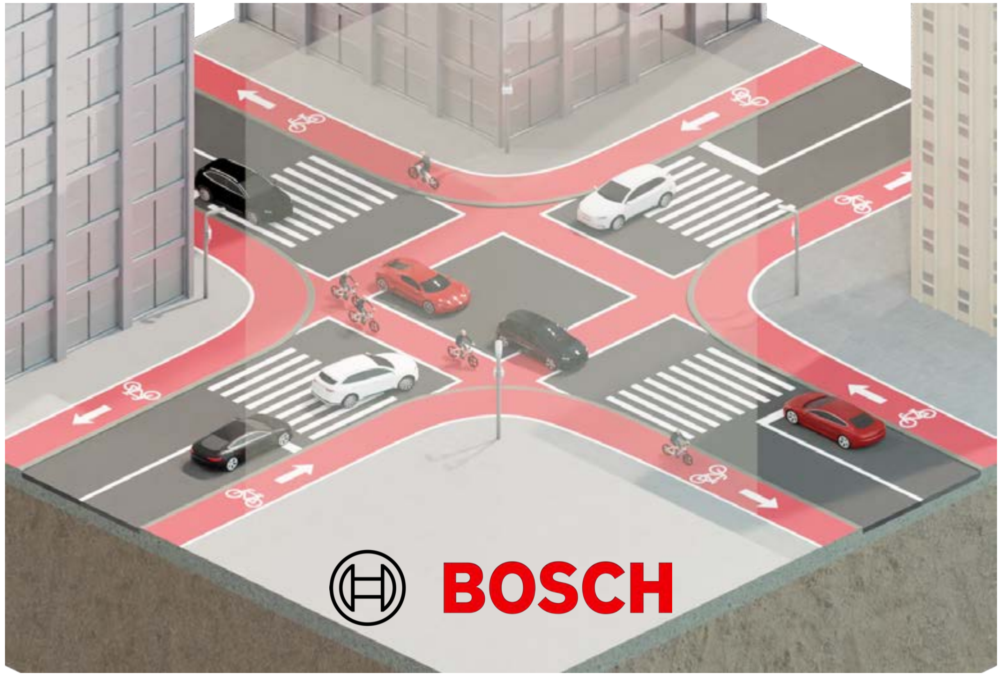
- Much hype for 100+ GHz: large bandwidths, excellent delay resolution.
- What about lower bands?



https://www.mpirical.com/blog/5g-radio-spectrum-and-wrc-19



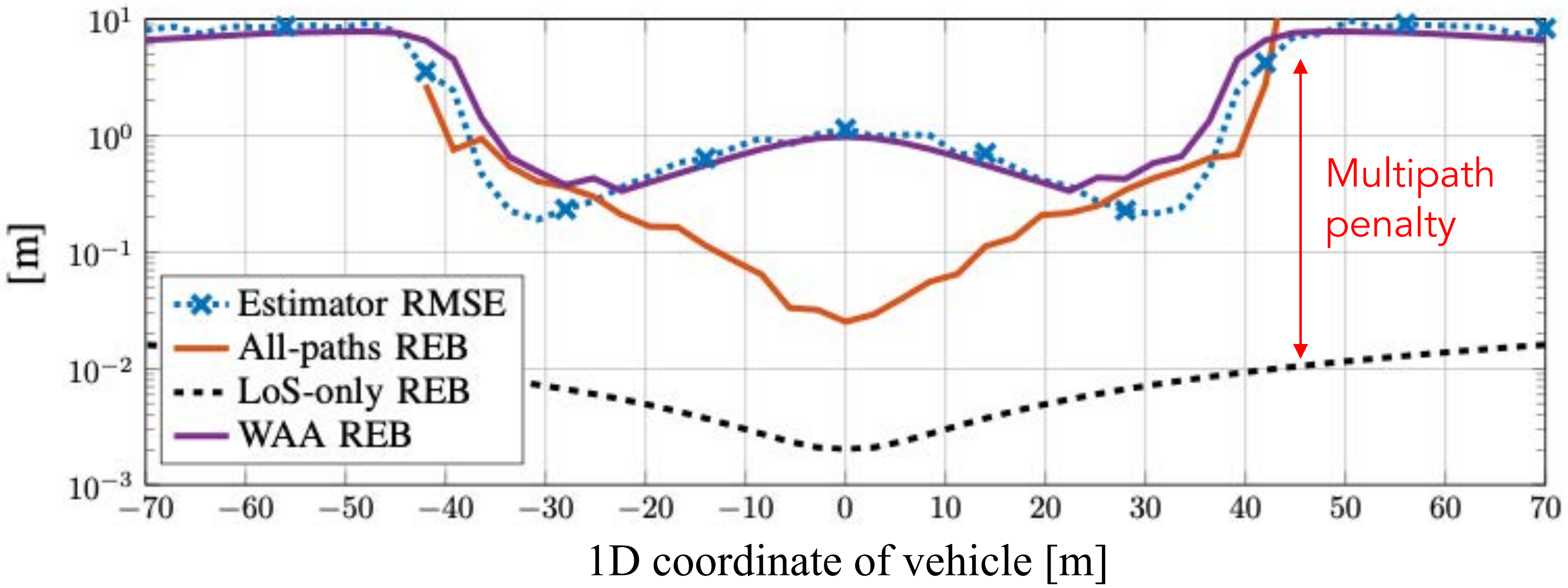
- Positioning and sensing perspective in lower bands
  - Penalty of limited bandwidth?
  - How to get resolution?



Ge, Y., Stark, M., Keskin, M.F., Hofmann, F., Hansen, T. and Wymeersch, H., 2023, March. Analysis of V2X Sidelink Positioning in sub-6 GHz. In 2023 IEEE 3rd International Symposium on Joint Communications & Sensing (JC&S).

Results from ray-tracing

- Ranging between fixed road-side unit and moving vehicle

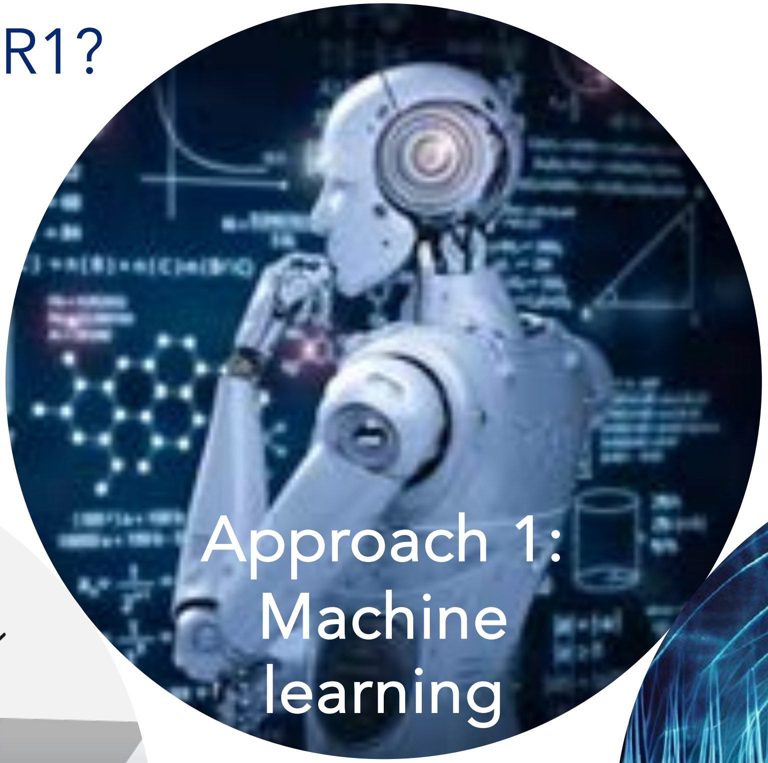


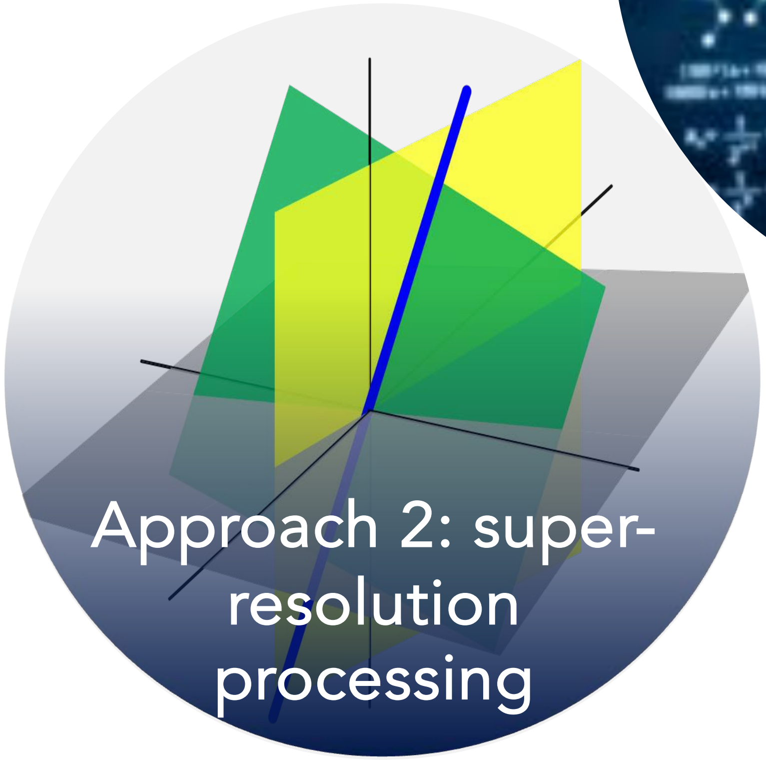
- Multipath interference is a limiting factor!
- Even worse for sensing (clutter).

Parameter	Setting
Transmitter	Single omnidirectional antenna
Receiver	Single omnidirectional antenna
Carrier frequency	5.9 GHz
Bandwidth	20 MHz in total, 167 subcarriers, 120 kHz subcarrier spacing
Poilt signal	OFDM, 12 symbols with a constant amplitude
Transmitter power	10 dBm
noise spectral density	−174 dBm/Hz
Receiver noise figure	8 dB
Number of RSU	1
Number of users	1 vehicle, 1 bicycle
RSU location	[0 0 10] meter
Landmarks	4 buildings
Sampling time	100 ms
Speed	Vehicle: 4m/s, bicycle: 1.4m/s

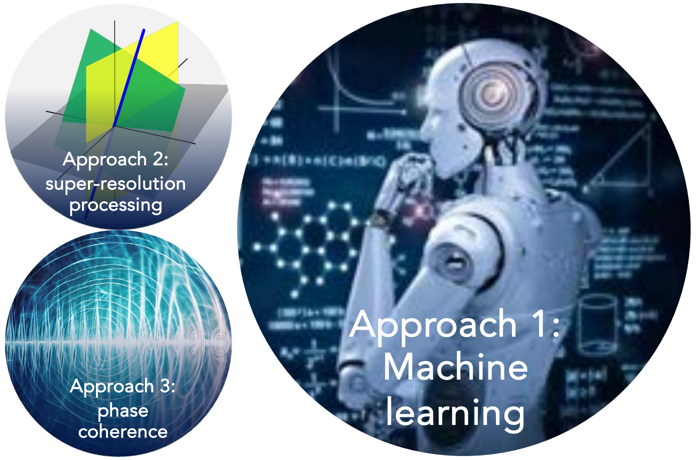
BOSCH

Improving resolution at FR1?

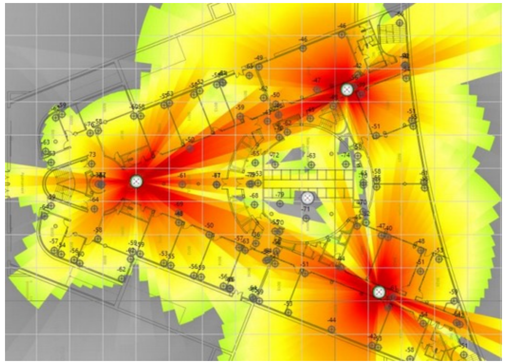




Machine learning: fingerprinting



- **Concept:**
  - Channel impulse response (CIR) unique for each location
  - Changes smoothly over space
  - Mapping from CIR to location can be learned (supervised learning)
- **Advantages:**
  - High resolution, richer channel helps
  - Relatively accurate (~ 1 meter)
  - Easy to use (inference)
  - Potential to augment model-based methods
- **Drawbacks:**
  - Difficult to train (data collection)
  - Sensitive to temporal variations
  - Non-explainable
  - Resolution not well-understood



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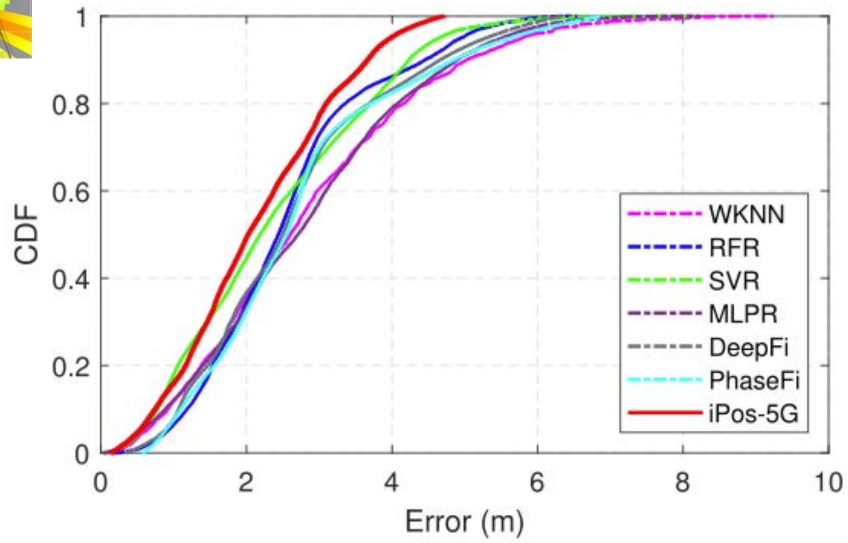
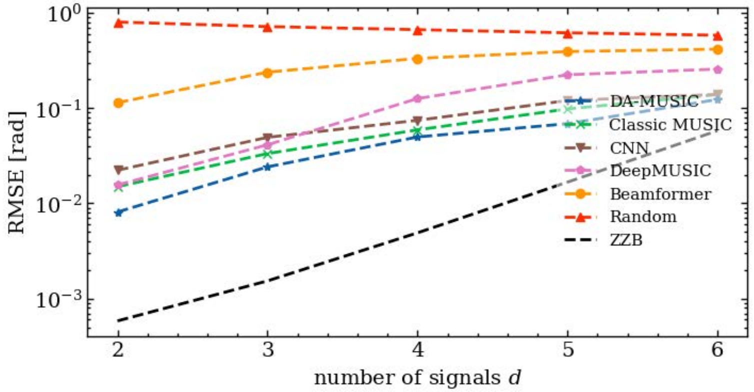
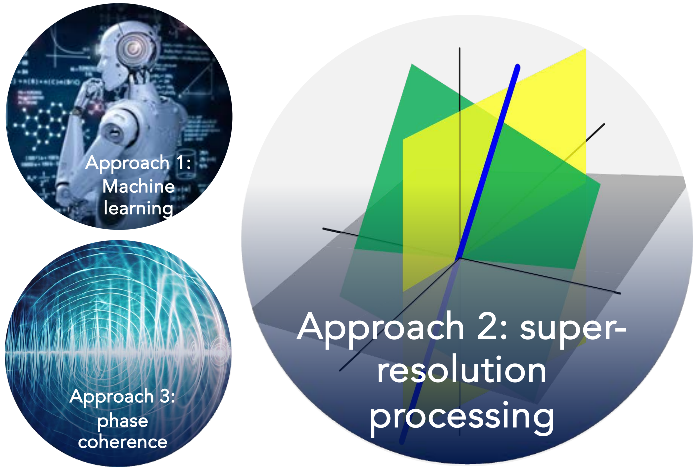


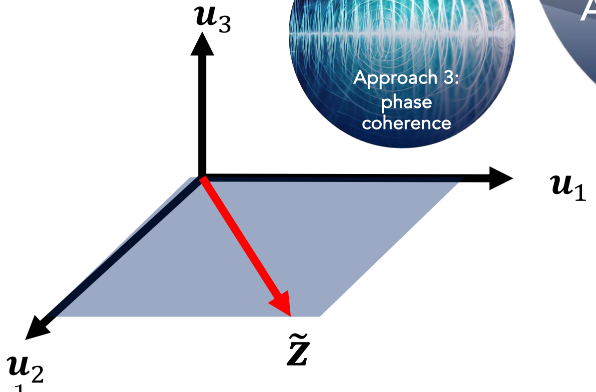


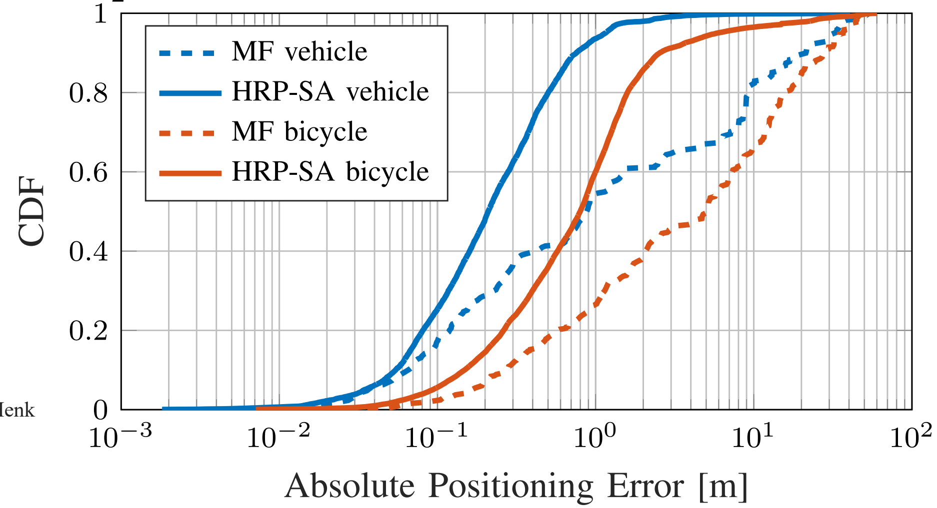
Merkofer, J.P., Revach, G., Shlezinger, N., Routtenberg, T. and van Sloun, R.J., 2023. DA-MUSIC: Data-driven DoA estimation via deep augmented MUSIC algorithm. IEEE Transactions on Vehicular Technology.

Super-resolution processing

- Concept:
  - Channel parameters span low-dimensional subspace, dimensionality depends on number of paths
  - Observation lies in high-dimensional subspace depends on number of subcarriers, snapshots, antennas
  - From separating signal and noise subspace, channel parameters (delays, angles, Dopplers) can be recovered
- Advantages:
  - Unlimited resolution
  - Sometimes search-free (ESPRIT)
- Drawbacks:
  - Need high SNR
  - Still complex for high dimensions (tensor processing)







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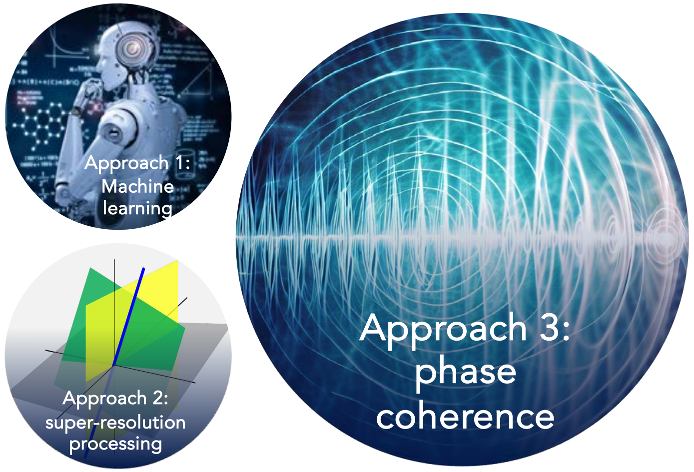
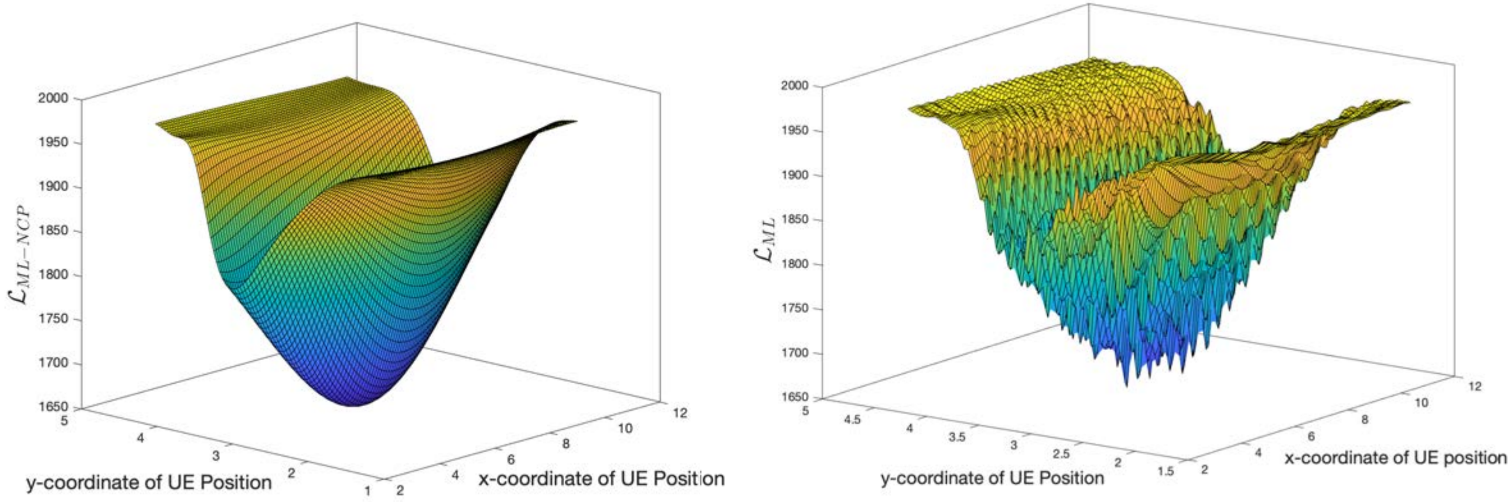
Phase coherence

- **Concept:**
  - Small resources (time, frequency, antennas) can be fused coherently
  - Provide larger aperture / aggregate bandwidth
  - Realizations: cell-free MIMO, carrier phase positioning, distributed radar
- **Advantages:**
  - Very high resolution
- **Drawbacks:**
  - Channel non-stationarity
  - Ambiguities
  - High complexity processing





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Outline

- Foundations of radio localization and sensing
- Localization in 5G: practice and potentials
- Integrated communication and sensing/localization towards 6G
- Main research questions and challenges

Conclusions and questions

- 6G will be first generation with localization and sensing built in from the start, but how will these services be used?
- High frequencies, large bandwidth, many antennas is an interesting regime.
- Lower bands should not be forgotten: high resolution from high SNR, phase coherence, or machine learning.
- Many challenges to make it work in practice.
- Exciting times:
  - ISAC beyond monostatic sensing, synergies and trade-offs.
  - RIS can be used to partially replace BSs for enabling localization.
  - Hardware limitations and calibration will be important limitation for positioning and radar.
  - What role will AI, NTN, … play?
  - KVIs (sustainability, trustworthiness, inclusiveness) must be considered in the design. How?

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- Thank to collaborators: G.Seco Granados, M. Valkama, V. Koivunen, A. Graell, C. Häger, S. He, B. Denis, G. Alexandropoulos, T. Al-Naffouri, F. Wen, and many others

- Follow our work on:
  - http://hexa-x.eu
  - https://hexa-x-ii.eu
  - https://rise-6g.eu
  - https://www.youtube.com/channel/UCuKdLuLXX0gs-OeZdbzOgsg
  - https://sites.google.com/site/hwymeers/

HORIZON 2020

VINNOVA Sweden's Innovation Agency

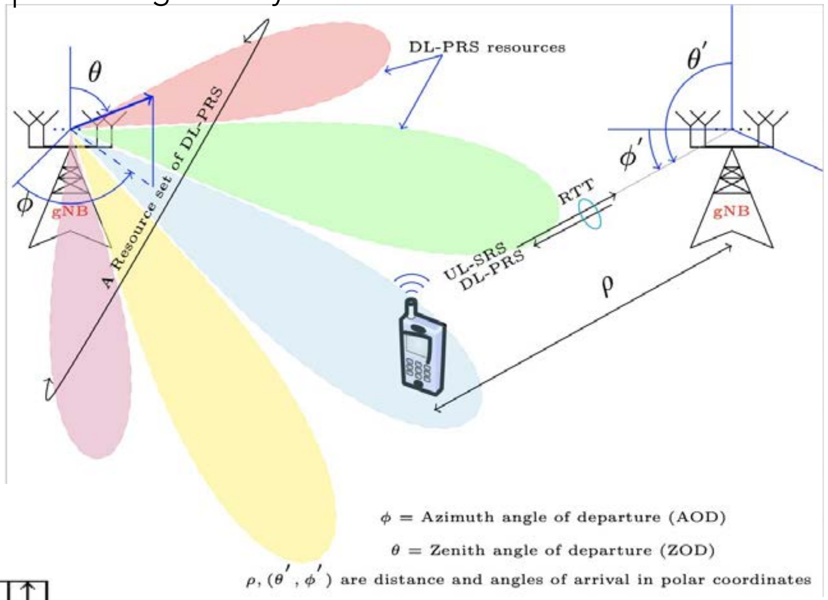
WASP WALLENBERG AI, AUTONOMOUS SYSTEMS AND SOFTWARE PROGRAM

Swedish Research Council

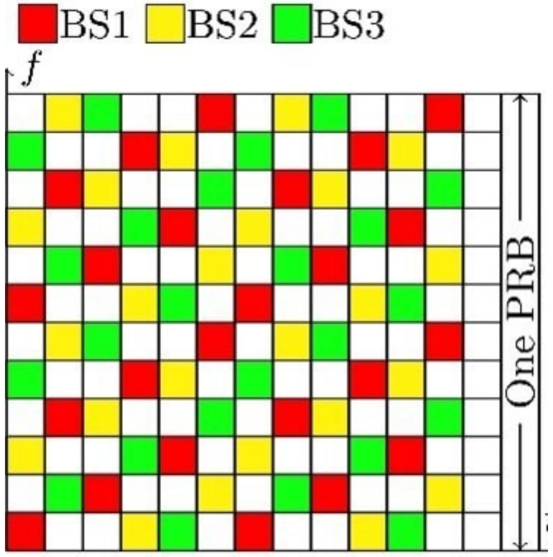
MARIE CURIE ACTIONS

Since 3GPP-R16, several enhancements

https://www.ericsson.com/en/blog/2020/12/5g-positioning--what-you-need-to-know



- Methods
  - UL and DL-TDOA
  - Multi-RTT
  - DL-AOD
  - UL-AOA
- Signals (broadcast)
  - Flexible positioning reference signals
  - Long and short duration
  - Several BSs supported via comb patterns
  - Coherent combining
  - Large bandwidth for good delay estimation
  - Combined with directional beams
- Outcomes
  - Sub-meter accuracy possible
  - Needs dense deployments
  - Time synch major bottleneck
  - Limited angle resolution, limited knowledge of beam patterns
  - Continuing work, increasingly important



(a) A PRS pattern

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Further updates in 3GPP

- Release 17
  - Enhancements to time and angle measurement (e.g., using several adjacent beams)
  - Multipath reporting and mitigation
  - Latency reduction (scheduling and short transmissions)
- Release 18, 5G Advanced
  - Sidelink positioning (RTT-based)
  - Integrity support
  - Bandwidth aggregation
  - Carrier phase positioning
  - Low power high accuracy and RedCap positioning
- Also being studied
  - Use of AI/ML
  - Radar-like sensing

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