Radio Positioning in 6G Communication Systems

Cooperative Multi-Monostatic Sensing

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Outline

- Introduction to ICaS
- Preliminaries on sensing
- Multi-Monostatic Sensing
- Results
- Conclusion

Introduction

- 6G is expected to provide high data rate, minimal latency, and cm-level positioning accuracy [1].
  - e.g., in autonomous driving, extended reality (XR), and digital twins.

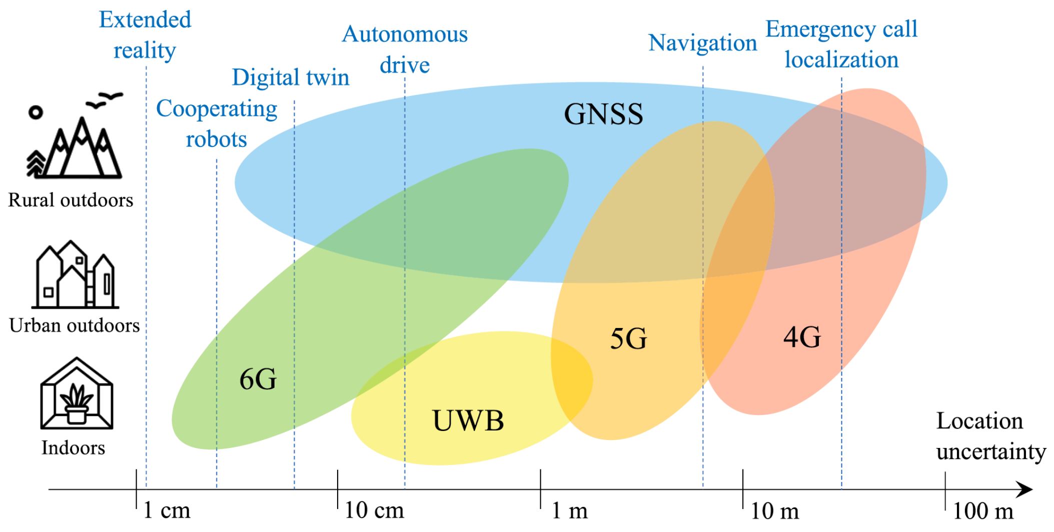


Fig. 1: Localization accuracies for different radio technologies in different environments [2].

- Positioning is the process of estimating the location and speed of a device/object from radio measurements
  - It could be active or passive
- Active Sensing: included in 3GPP.
  - In the cellular network, there are the PRS (Positioning reference signal) and SRS (sounding reference signal).
- Passive Sensing: not yet included.
  - Monostatic, Bistatic, Multistatic Sensing

[1] A. Zhang, M. L. Rahman, X. Huang, Y. J. Guo, S. Chen and R. W. Heath, "Perceptive Mobile Networks: Cellular Networks With Radio Vision via Joint Communication and Radar Sensing," in IEEE Vehicular Technology Magazine, vol. 16, no. 2, pp. 20-30, June 2021, doi: 10.1109/MVT.2020.3037430.
[2] H. Wymeersch and G. Seco-Granados, "Radio Localization and Sensing—Part II: State-of-the-Art and Challenges," in *IEEE Communications Letters*, vol. 26, no. 12, pp. 2821-2825, Dec. 2022.

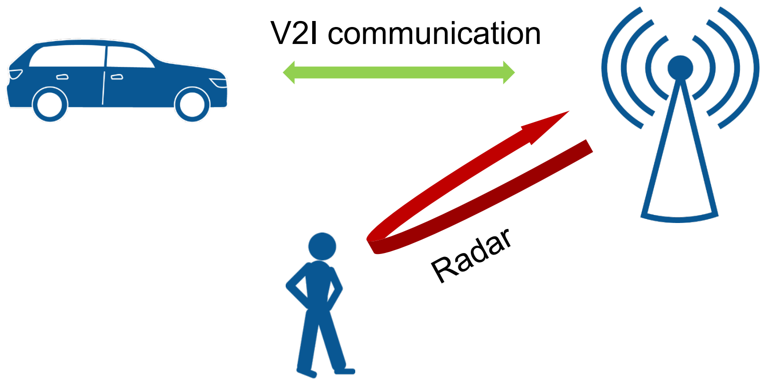
ICaS: two functions one system

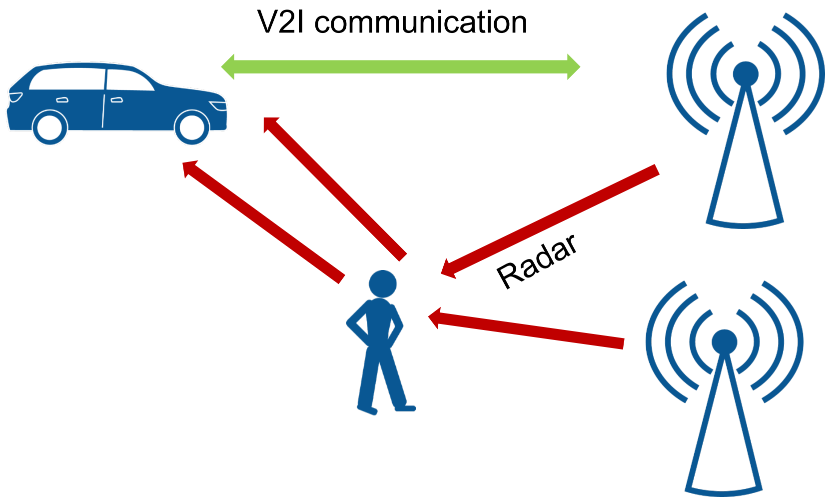
- Enablers
  - More bandwidth at mmWave frequencies
  - Hardware, signal and radio resource re-use
  - Massive MIMO
  - AI-based designs and algorithms
- Challenges
  - Hardware impairments
  - Power consumtion
  - Deployment cost
  - Satisfying accuracy for plethora of use cases
  - Trade-off between coms and sesnig KPIs

Sensing Perspective	Communication Perspective
Probability of Detection	Throughput
Range Resolution	Latency
Velocity Resolution	Spectral Efficiency
Maximum Unambiguous Range	Energy Efficiency
Maximum Unambiguous Velocity	Number of Served Users
Estimation Accuracy	Bit Error Rate

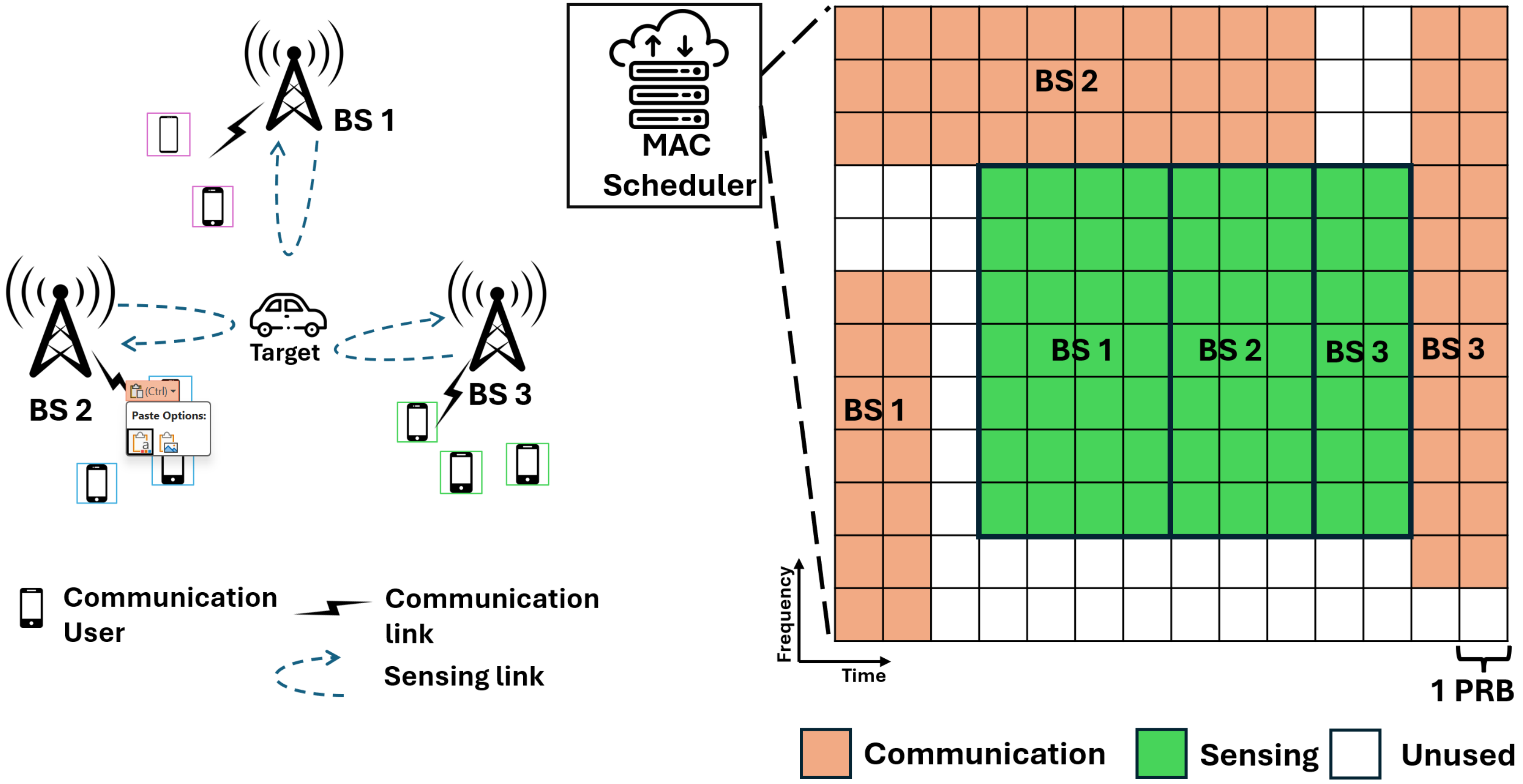
Types of Sensing

- Monostatic Sensing
  - Coherent Signal Processing
- Bistatic Sensing.
  - Large angles of observation
  - Coherent operation difficult
- Multistatic Sensing
  - Increased target information
  - Increased probability of detection
  - Coherent operation difficult





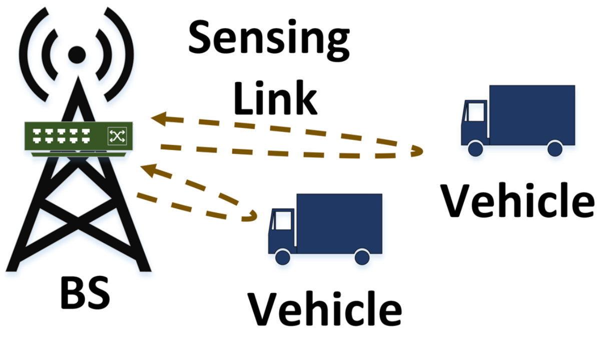
Resource sharing



OFDM Radar Use Case

Analyzed KPIs:

- Range resolution
- Velocity resolution
- Maximum Unambiguous Range/Velocity

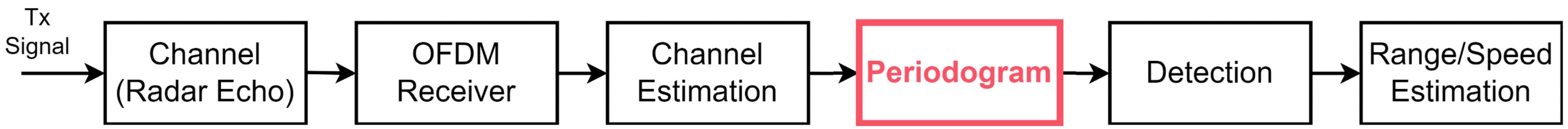


System model

- Single BS used as a monostatic radar.
- Two targets being detected.
- No clutter and no interference was assumed.

Radar receiver

- Periodogram method [3] for range and speed estimation.



[3] K. M. Braun, "*OFDM radar algorithms in mobile communication networks*," Doctoral dissertation, Karlsruhe, Karlsruher Institut für Technologie (KIT), Diss., 2014.

Simulation Parameters

Parameter	Value	
Band	Sub-6GHz	mmWave
MonteCarlo No	1000	
f_c (MHz)	3500	28000
Δf (kHz)	$\{15, 30, 60\}$	$\{60, 120\}$
OFDM Numerology	3GPP 38.211	
Field Dimensions*	$35 \le R \le 200\ (m)$, $-30° \le \Theta \le 30°$	$14 \le R \le 800\ (m)$, $-30° \le \Theta \le 30°$
AP Position	$(X, Y) = (0, 0)$, $h = 7m$	$(X, Y) = (0, 0)$, $h = 3.75m$
AP antenna gain (dBi)	17.5	24
Channel model	LOS Channel (open field)	
Noise power (dBm)	$-174 + 10\log_{10}(\Delta f N_{sc}) + 7$	

Parameter	Value
Radar type	OFDM Radar (QPSK)
Total BS power	$43dBm$
$P_{sensing}$	0.1
Detection method	Periodogram + peak detection
No. of targets	2
Target max velocity**	$\min(150kph, v_{ICI}, v_{mig})$
Target RCS	$1m^2$

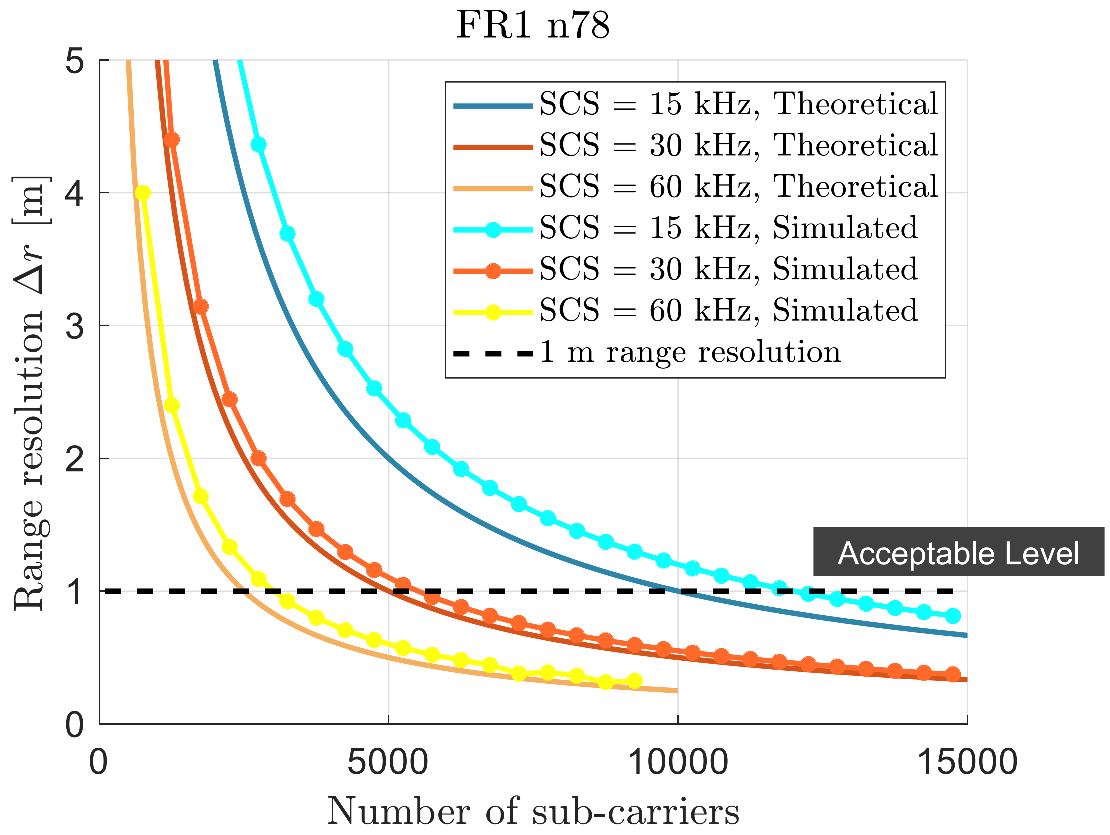
*$R \ge d_{ISI} = \frac{cT_{CP}}{2}$ was not considered.

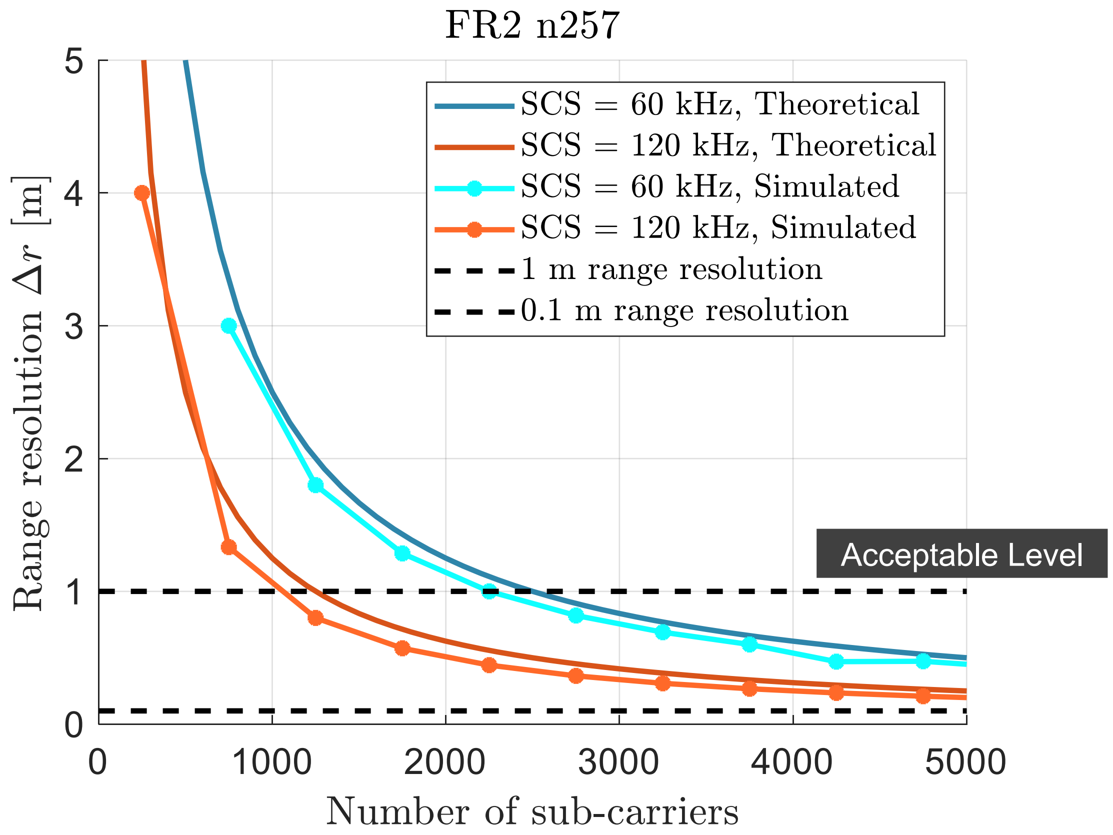
**$v_{ICI} \triangleq \frac{(0.1SCS)c}{2f_c}, \ v_{mig} = \frac{c}{4N_{sc}N_{OFDMsym}\Delta f T_{sym}}$

Range Resolution Estimation	
Parameter	Value
$N_{subcarriers}$	$\{25\ 50\ 100{:}\ 100{:}\ 3300\}$
Measurement duration	1 slot (N_{sym}^{slot} symbols)
FFT size	$4N_{subcarriers}$

Velocity Resolution Estimation	
Parameter	Value
N_{sc}	120 (10 Resource Blocks)
Measurement duration	$\{5\ 10\ 15\ 20\ 25{:}\ 25{:}\ 500\}$ OFDM symbols
FFT size	$4N_{OFDMsymbols}$

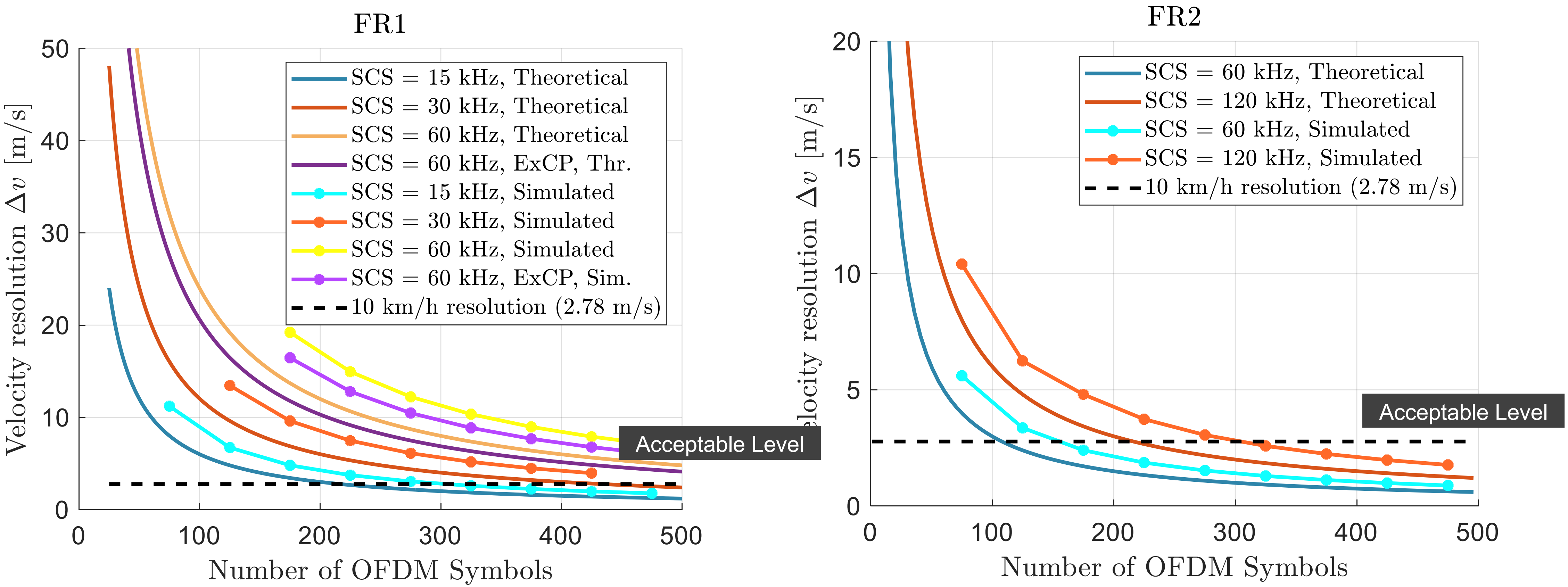
Range Resolution - Number of Subcarriers





- With lower subcarrier spacing, we need higher number of subcarriers to achieve the desired range resolution. To achieve $\Delta r = 1\ \mathrm{m}$, $\mathrm{BW} = 150\ \mathrm{MHz}$ is needed.
- FR2 spectrum band is better than FR1 for stringent range resolution scenarios

Velocity Resolution - Number of OFDM Symbols



- With lower subcarrier spacing, higher number of OFDM symbols are need to achieve the desired velocity resolution.

Maximum Unambiguous Velocity and Range

Table 1: Maximum unambiguous range for different numerologies.

Band	Δf (kHz)	T_{CP} (μs)	R_{max} (m)
FR1	15	4.7	700
	30	2.3	345
	60	1.2	180
	60 $(Ext.CP)$	4.1	620
FR2	60	1.2	180
	120	0.6	90

Table 2: Maximum unambiguous velocity for different numerologies.

Band	Δf (kHz)	$f_{D,max}$ (Hz)	$\Delta f / f_c$	v_{max} (m/s)
FR1	15	1500	$4.3e-6$	64
	30	3000	$8.6e-6$	129
	60	6000	$17.1e-6$	257
FR2	60	6000	$2.1e-6$	32
	120	12000	$4.3e-6$	64

Monostatic sensing: challenges

- In passive sensing there are some challenges to address

  1. There is a bias in the estimation due to the multipath components.
  2. The accuracy of the measurements depend on the number of non-line-of-sight components.
  3. It is challenging to distinguish between multiple targets and “false” targets created by multipath.

- One possible solution is by taking advantage of the network densification in 6G and using multiple BSs cooperatively, where each BS acts as a monostatic radar, building the called multi-monostatic sensing.

System Model

- K base stations
  - All synchronized
  - Connected to a Central Processing Unit (CPU)
- OFDM waveform under 5G NR
  - M OFDM symbols
  - N active subcarriers
- Single target moving throughout the street
- Distance and position estimation

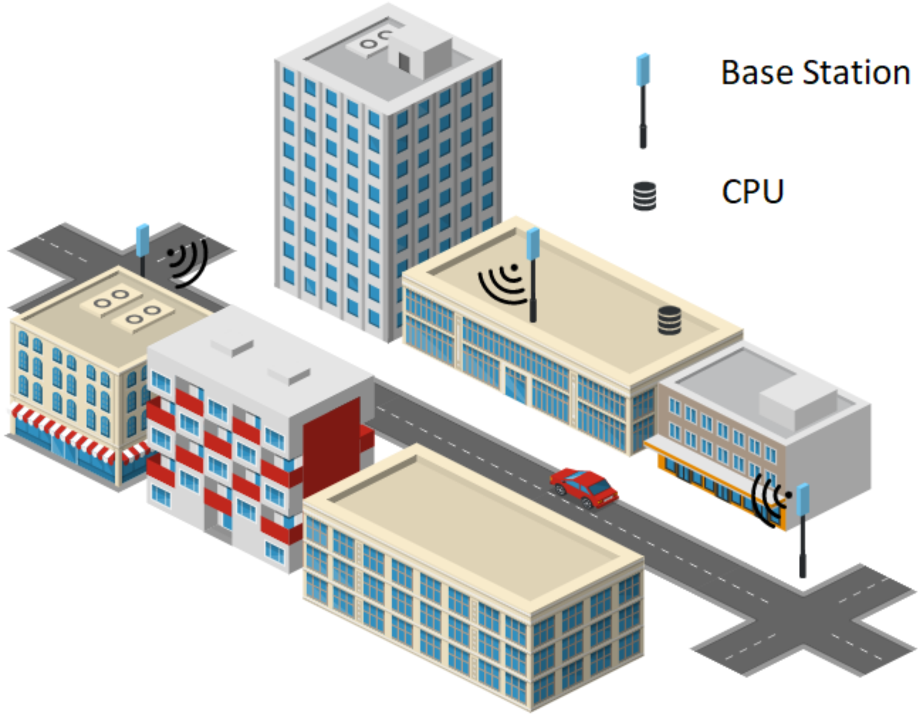


Fig. 2: System Model

Monostatic Sensing: Channel Model

- Ray Tracing MATLAB simulator

- Section of Berlin (.osm file):
  - Red: BS
  - Blue: Target

- The number of reflections (N_R) can be set.
  - Figure 2: $N_R \leq 1$

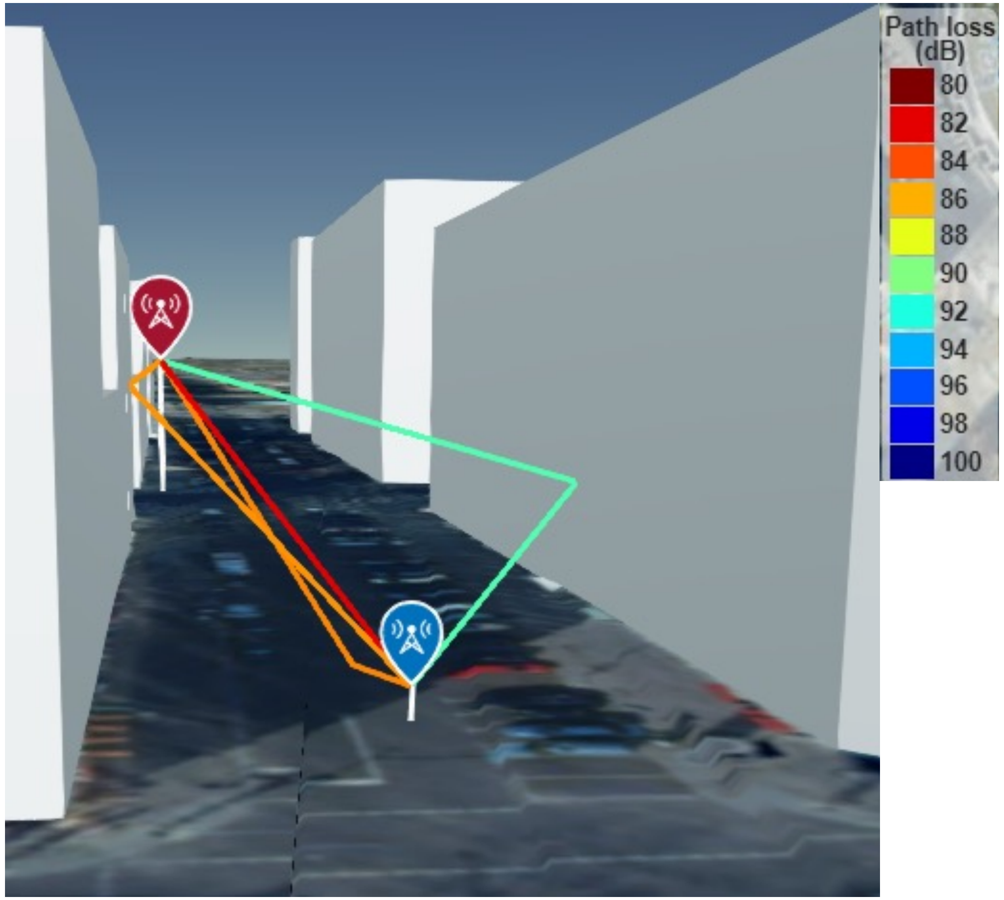


Fig. 3: Ray Tracing Simulator

Monostatic Sensing: Periodogram

- Periodogram algorithm used to estimate distance:

$$A(n,m) = \left| \sum_{r=0}^{N'-1} \sum_{l=0}^{M'-1} \left(D_{r,l}\, e^{-j2\pi\, l\, m/M'} \right) e^{j2\pi\, r\, n/N'} \right|^2$$

- Estimated distance and speed are given by:

$$\hat{d} = \frac{\hat{n} c_0}{2\, \Delta f\, N'}, \quad \hat{v} = \frac{\hat{m} c_0}{2\, f_C\, T\, M'}$$

where $\hat{n}$, $\hat{m}$ are estimated as:

$$(\hat{n}, \hat{m}) = \arg\max_{n,m} A\,(n,m)$$

$D_{r,l}$: Received signal after zero-forcing
$M' \geq M$ (M OFDM symbols)
$N' \geq N$ (N active subcarriers)
Δf : Subcarrier spacing
f_C : Carrier frequency
T: overall OFDM symbol duration

Monostatic Sensing: Effect of Multipath

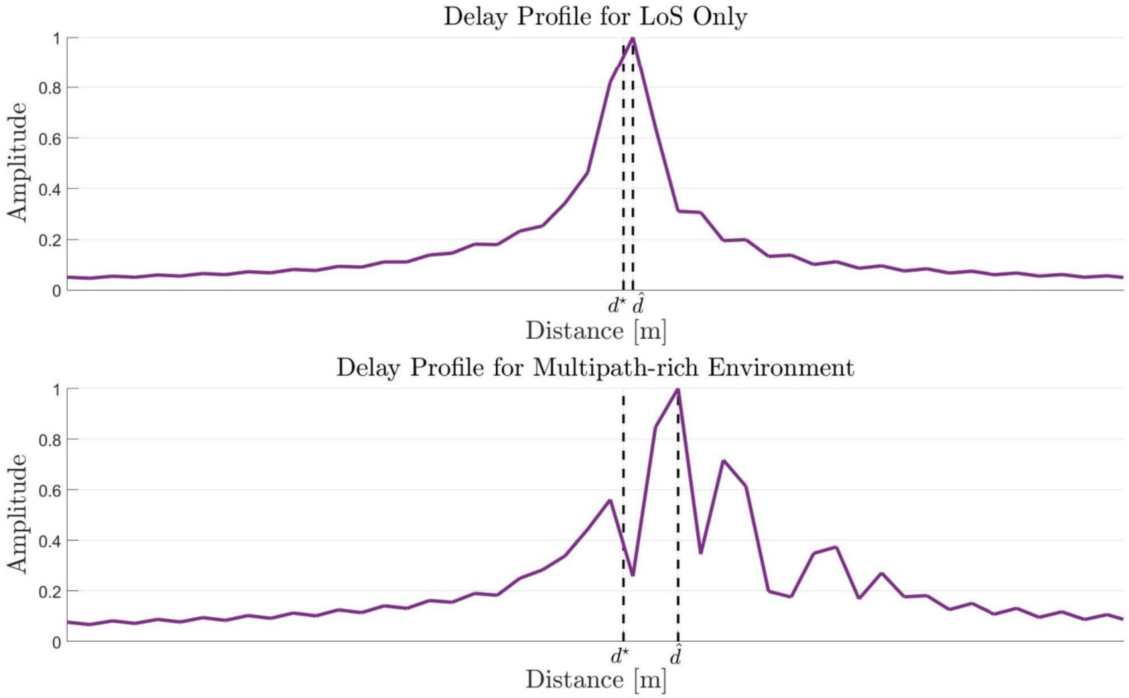
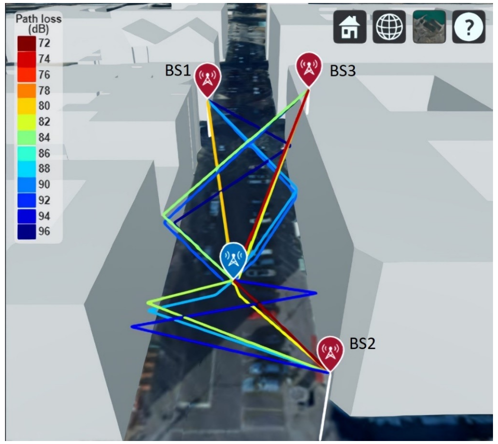


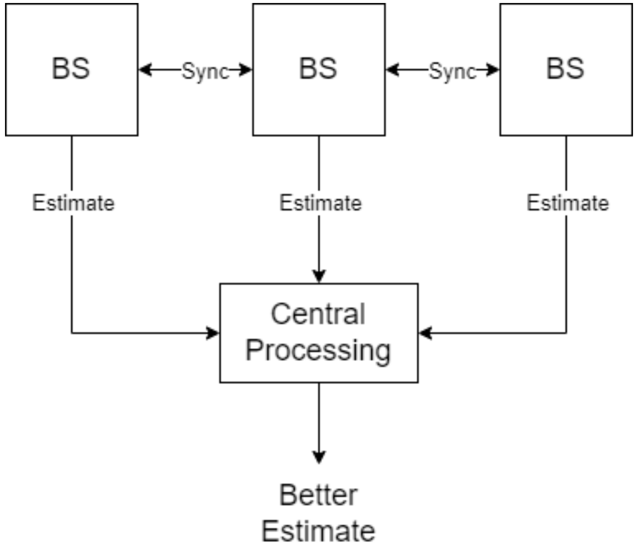
Fig. 4: Delay profile comparison between a LOS-only and a multipath-rich environment

- From the figure, the error $|\hat{\mathrm{d}} - \mathrm{d}^\star|$ increases for multipath-rich environment, where
  - $\hat{\mathrm{d}}$ is the estimated distance
  - $\mathrm{d}^\star$ is the true distance
- The more paths considered, the more difficult to detect the real target.

Multi-monostatic Sensing [2]

- K base stations
  - All synchronized
  - Connected to a Central Processing Unit (CPU)
- Each BS estimate the distance
- A fusion method is run in a CPU:
  - The estimated distances $\widehat{d_k}$ are fused.
  - The position of the target $\mathbf{x}$ is obtained.
- Three fusion algorithms are studied:
  - Maximum Likelihood
  - Maximum A Posteriori
  - Non-linear Least Square





[2] M. R. Figueroa, P. K. Bishoyi, and M. Petrova, "Cooperative Multi-Monsotatic Sensing for Localization in 6G," in IEEE WCNC 2024, Dubai, UAE.

Multi-monostatic Sensing: Fusion Algorithms

- Maximum Likelihood (ML)

$$\hat{x}_{LL} = \arg\max_{x} \sum_{k \in \mathcal{K}} w_k \cdot \ln\left(\frac{1}{\sqrt{2\pi}} \cdot \exp\left[-\frac{\left(\widehat{d_k} - ||x_k - x||\right)^2}{2\,\sigma_k^2}\right]\right) = \arg\max_{x} \sum_{k \in \mathcal{K}} w_k \cdot \ln(p_k(x))$$

- Maximum a Posteriori (MAP)

$$\hat{x}_{MAP} = \arg\max_{x} \sum_{k \in \mathcal{K}} w_k \left[\ln(p_k(x)) + \ln\left(\frac{1}{||x - x_k|| + \epsilon}\right)\right]$$

- Non-linear Least Square (NLLS)

$$\hat{x}_{NLLS} = \arg\min_{x} \sum_{k \in \mathcal{K}} w_k \left(\widehat{d_k} - ||x_k - x||\right)^2$$

  – σ_k^2: Gaussian component of the k-th BS.
  – w_k: weight for the k-th BS.
  – $\widehat{d_k}$: estimated distance of the k-th BS.

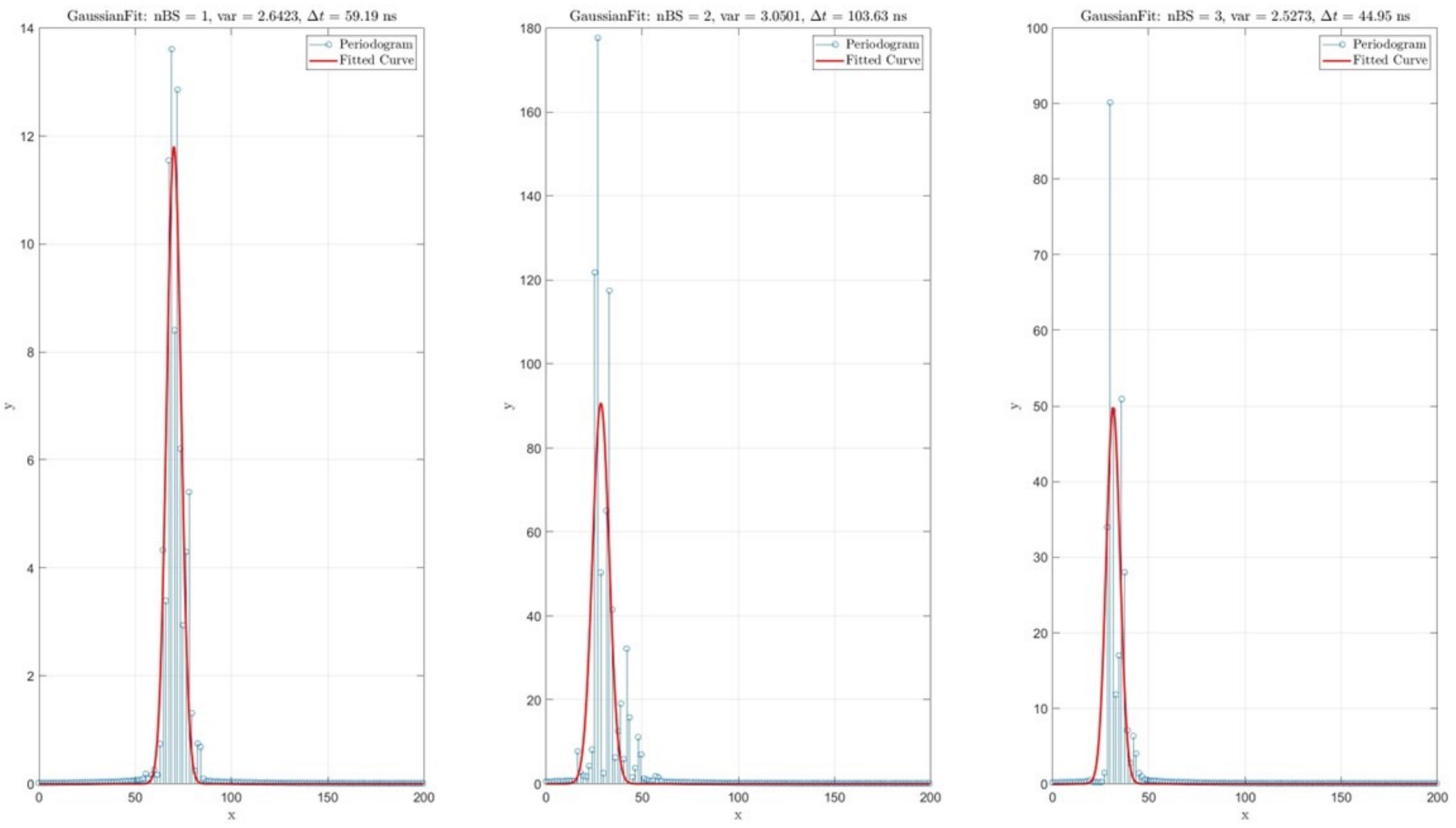
Multi-monostatic Sensing: Fusion

- The parameters are estimated by doing a Gaussian fit over the periodogram output:

  – The mean is used for $\widehat{d_k}$

  – The variance is used for σ_k^2.

  – The amplitude is used for w_k

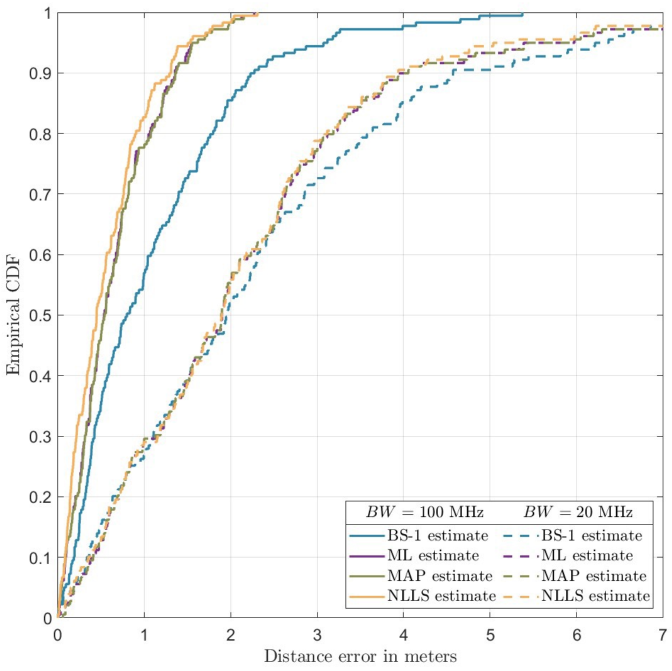


Simulation Parameters

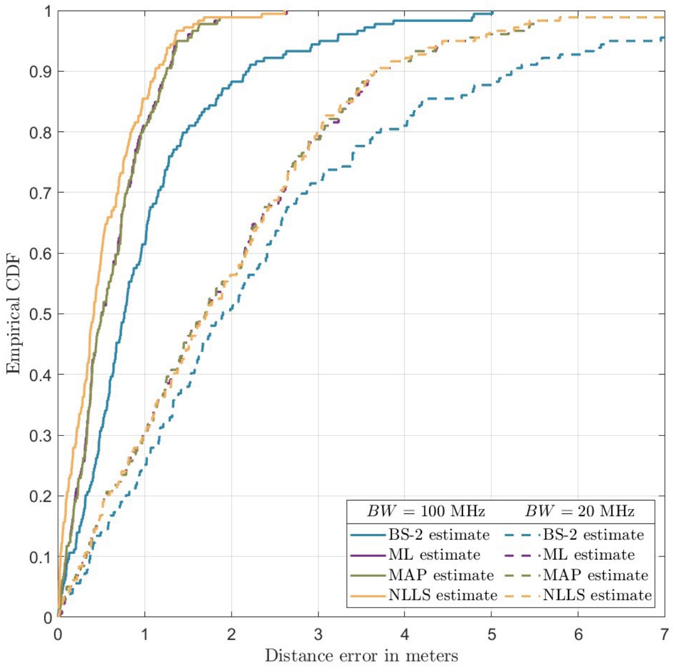
Parameters	Value
Bandwidth	20 and 100 MHz
Carrier Frequency	3.5 GHz
Radar Transmit Power	$P_T = 23 \text{ dBm}$
Antennas (Rx, Tx)	Omnidirectional
SCS	30 kHz
Vehicle speed	$\approx 50\ km/h$
Number of subcarriers	666 and 3333
Number of Symbols	500 (≈2 frames)
Number of BSs	Up to 3
Vehicle height	$1\ m$
Target RCS	$7\ dBsm$

- Range resolution: $1.5\ m$
- Velocity resolution: $2.4\ m/s$

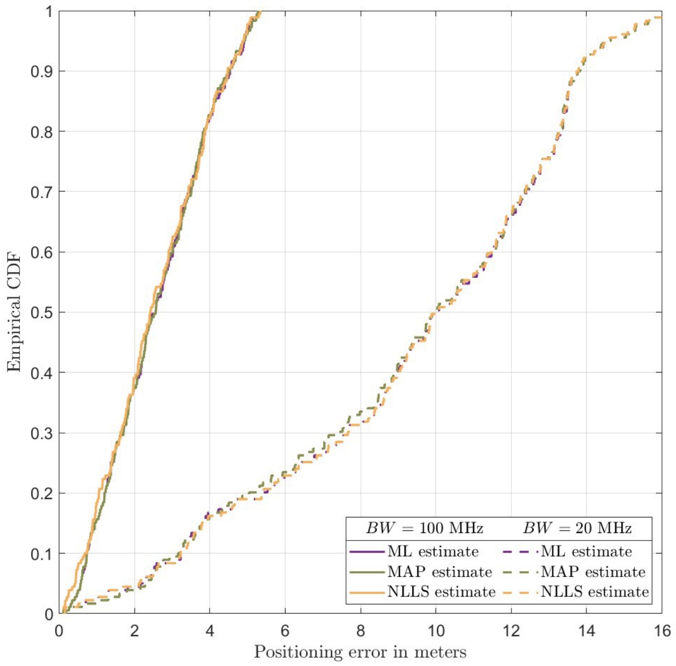
Results: 2 BSs Case



Distance error from BS1



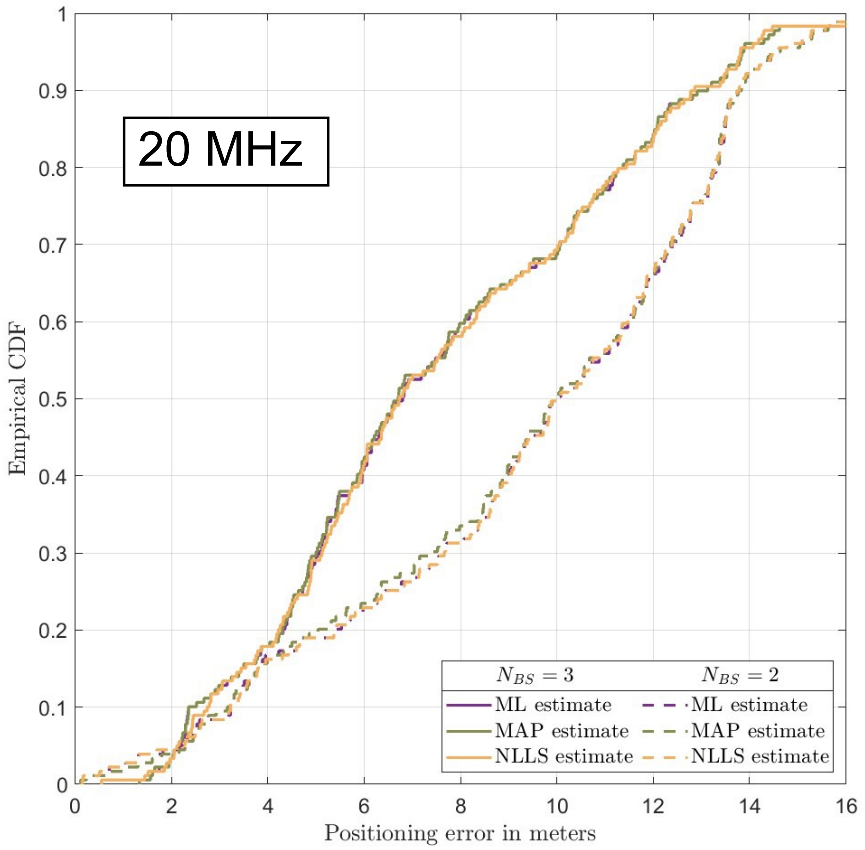
Distance error from BS2

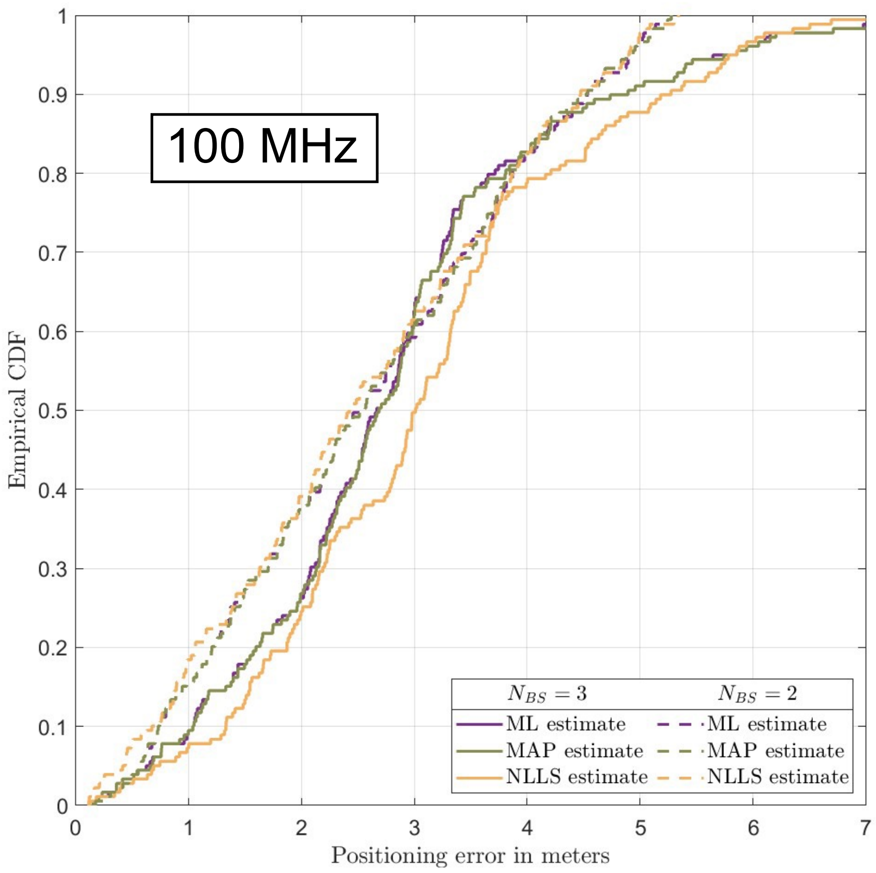


Positioning error for K = 2

- Depending on the BS location, there is different gain in the fusion output.

Results: Comparison of fusion for 2 and 3 BSs





- There is a considerable gain under limited BW
- However, there is no gain under 100 MHz, as BS3 is not giving accurate estimates due to multipath.

Findings

- Multi-monostatic sensing increases the accuracy of the estimation by combining the individual estimates of each BSs.
- Increasing the BW leads to less accuracy error in distance and positioning error.
- Under low resolution, the fusion of BSs' estimates can result in higher accuracy.
- Under higher resolution, the gain in the accuracy is dependent on the location of the BSs, where based on the multipath condition, each BS contributes more or less to the fusion gain.

Monostatic Sensing: Effect of Multipath (ToA + AoA)

- Adding an antenna array gives the AoA information.
- We use a uniform rectangular array of 8x8 antennas with FoV of $[-60°, 60°]$.
  - Beamwidth of $12°$
  - Gain of 22 dBi
- We can do beam scanning to sense the entire environment.
- By performing the periodogram on each angle of the beam scanning phase, we can estimate the position of the target (figure 4).

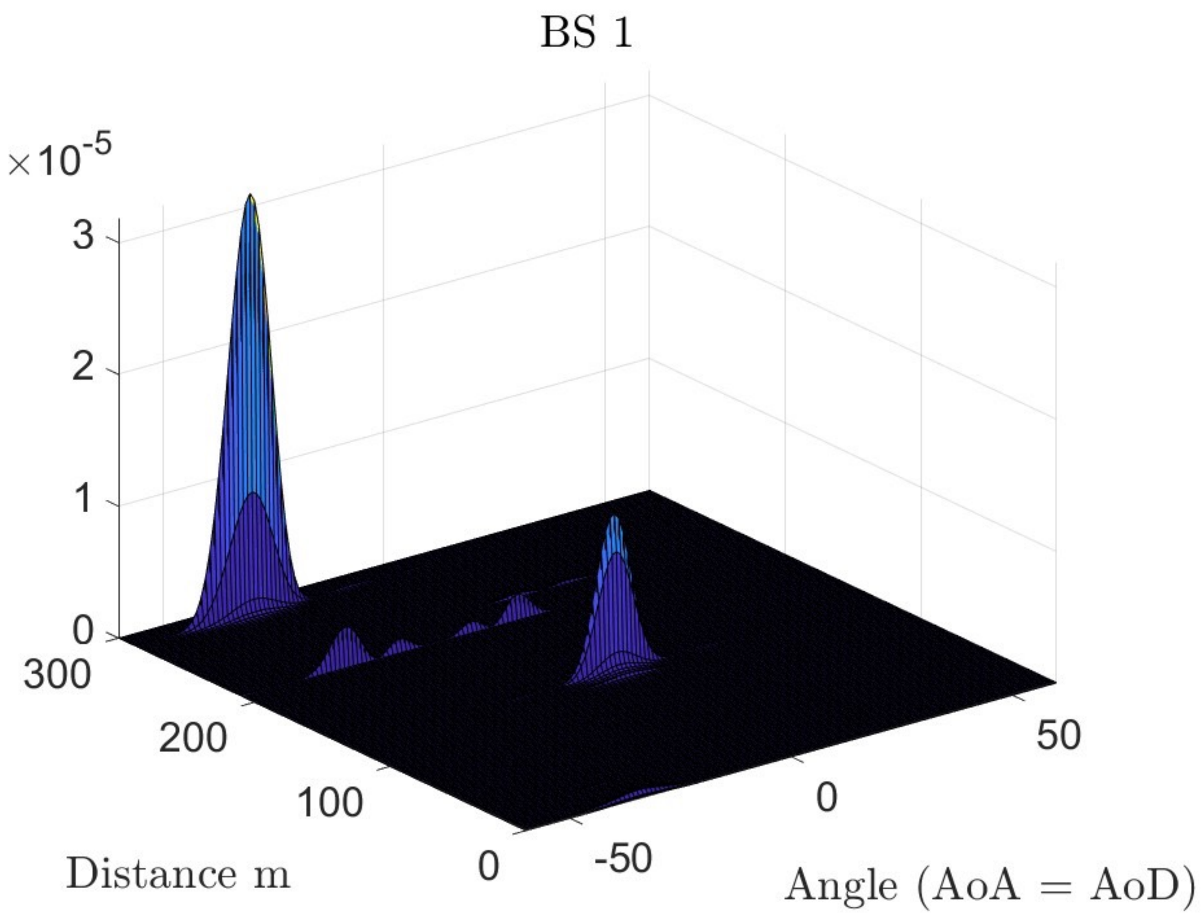


Figure 4: Periodogram map of distance and angle information.

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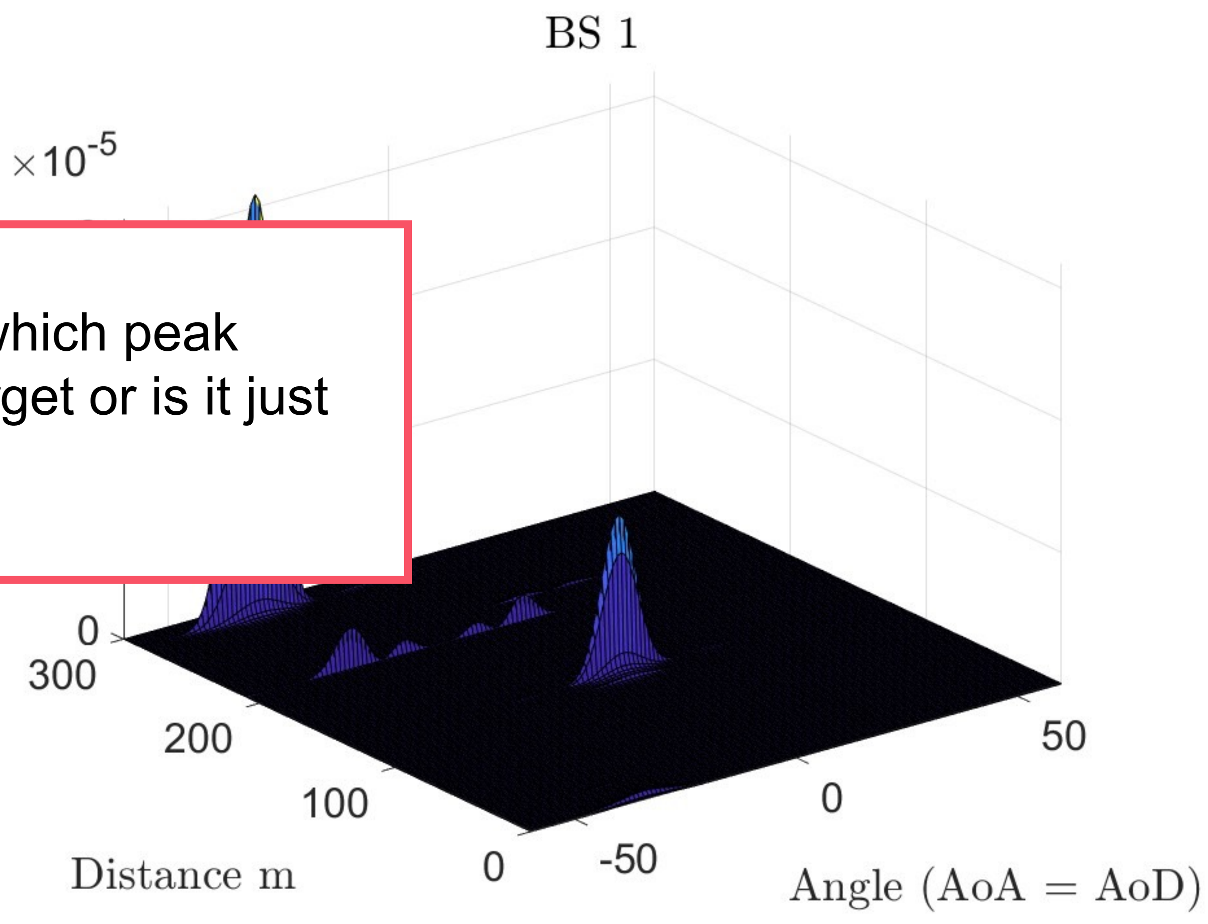
- How do we know which peak correspond to a target or is it just multipath?



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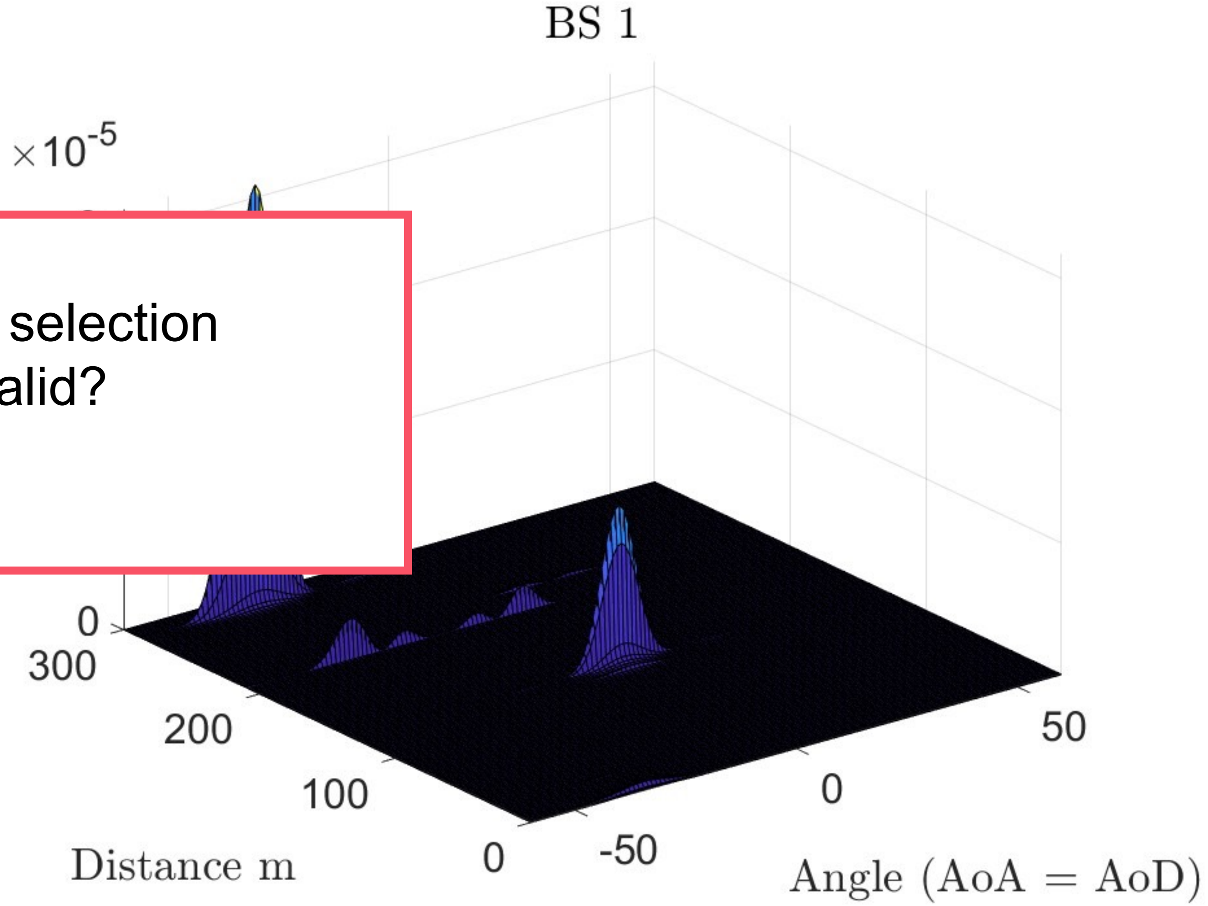
- Is the current peak selection method used still valid?



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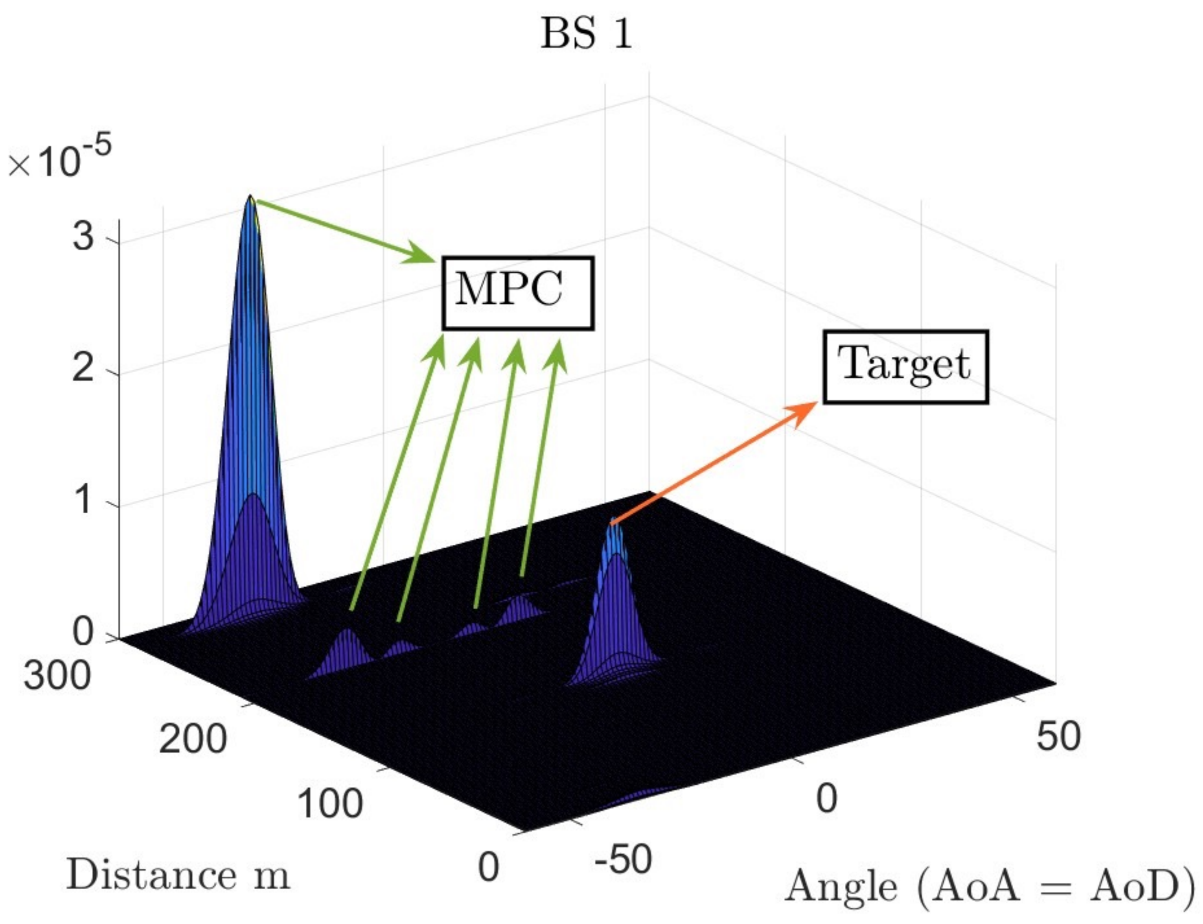
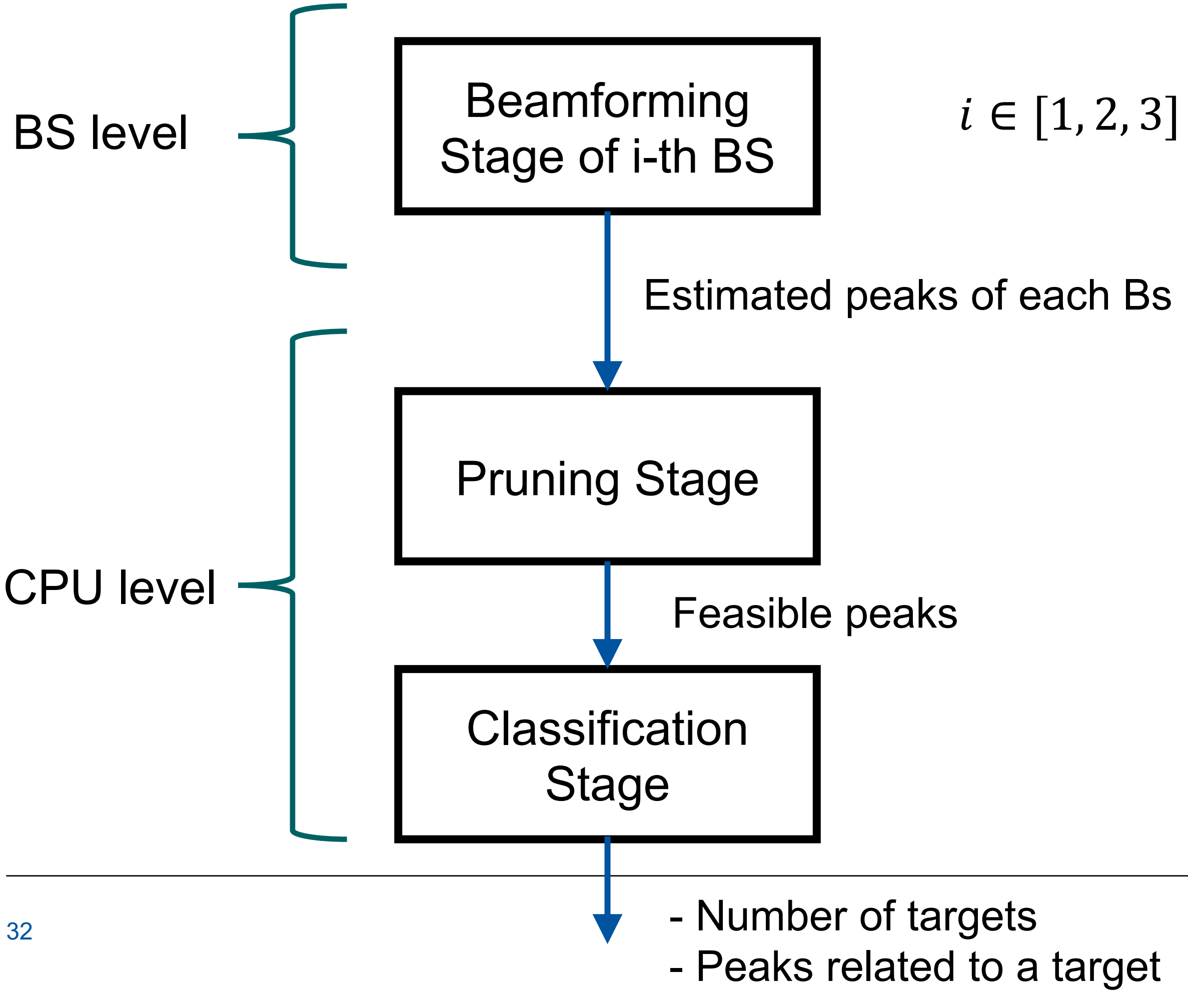


Figure 4: Periodogram map of distance and angle information.

Scenario and Proposed Algorithm

- In order to estimate the target and overcome multipath, a 3-stage algorithm is proposed:



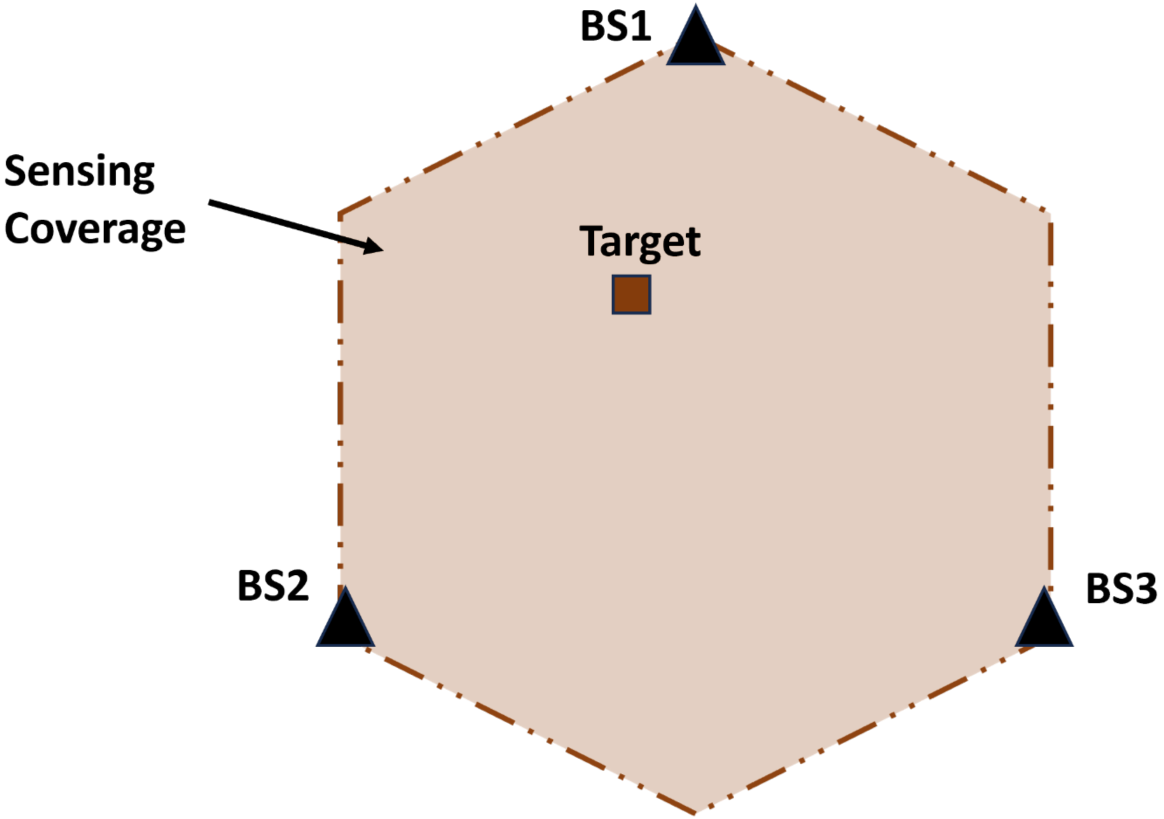


Figure 6: Scenario for the simulations. The three BSs build a convex-hull for the sensing coverage, given by the field of view of the antenna arrays.

Scenario and Proposed Algorithm

- In order to estimate the target and overcome multipath, a 3-stage algorithm is proposed:

1. Beamforming Stage
   - Each BS sense the environment over a range of $[\theta_{min}, \theta_{max}]$ and computes the periodogram for each angle step.
   - All the peaks found on the map (AoA - Range) are shared to a CPU.

2. Pruning Stage
   - All infeasible peaks are removed from the map.

3. Classification Stage
   - All the peaks are classified and assigned.
   - The number of targets is estimated.

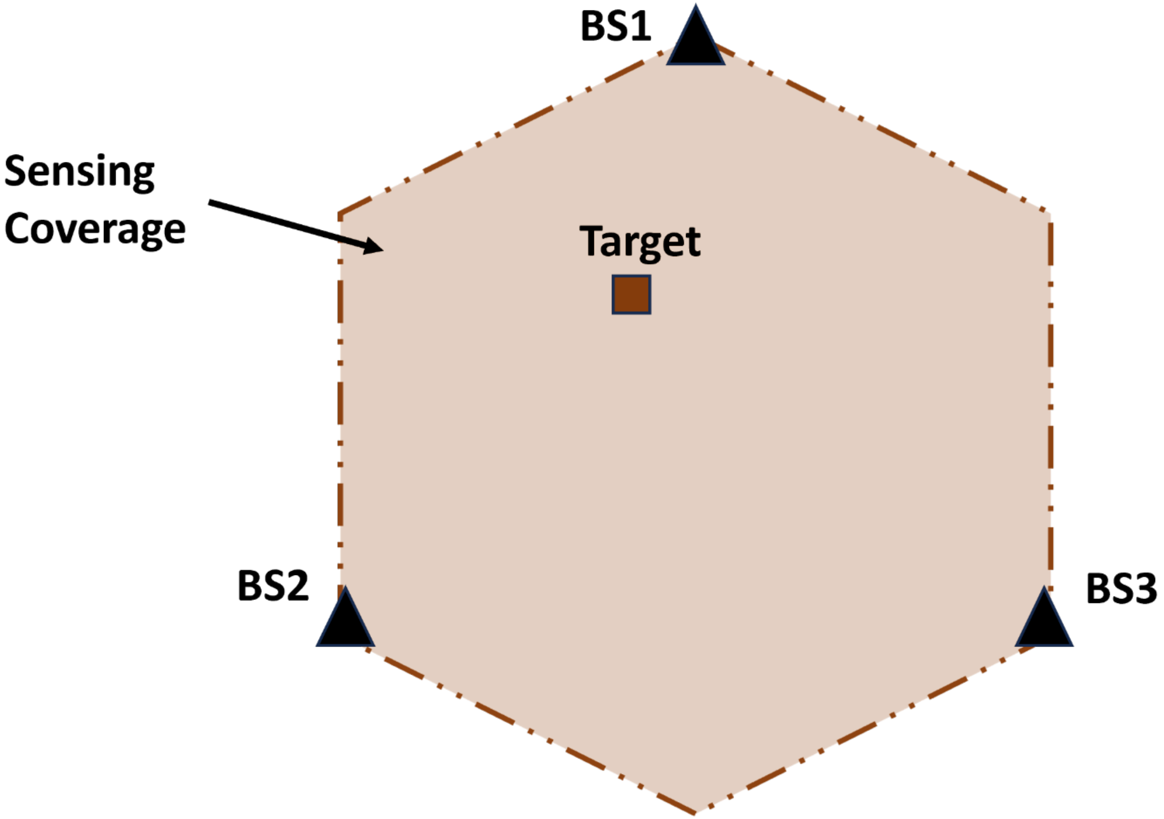


Figure 6: Scenario for the simulations. The three BSs build a convex-hull for the sensing coverage, given by the field of view of the antenna arrays.

Simulation Parameters

Parameters	Value
Bandwidth	100 MHz
Carrier Frequency	3.5 GHz
Transmit Power	$P_T = 49$ dBm
Antennas (Rx, Tx)	URA 8x8
Field of View	$[-60°, 60°]$
SCS	30 kHz
Number of BSs	Up to 3
Target height	$1\ m$
Target RCS	$7\ dBsm$

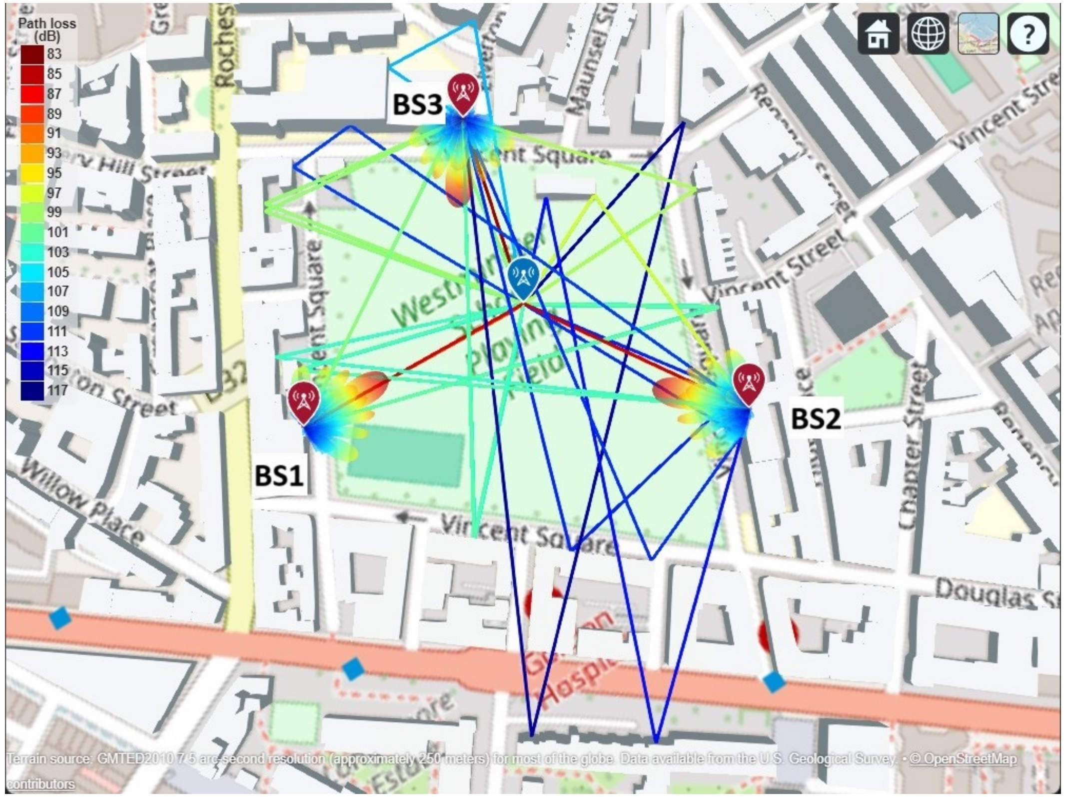
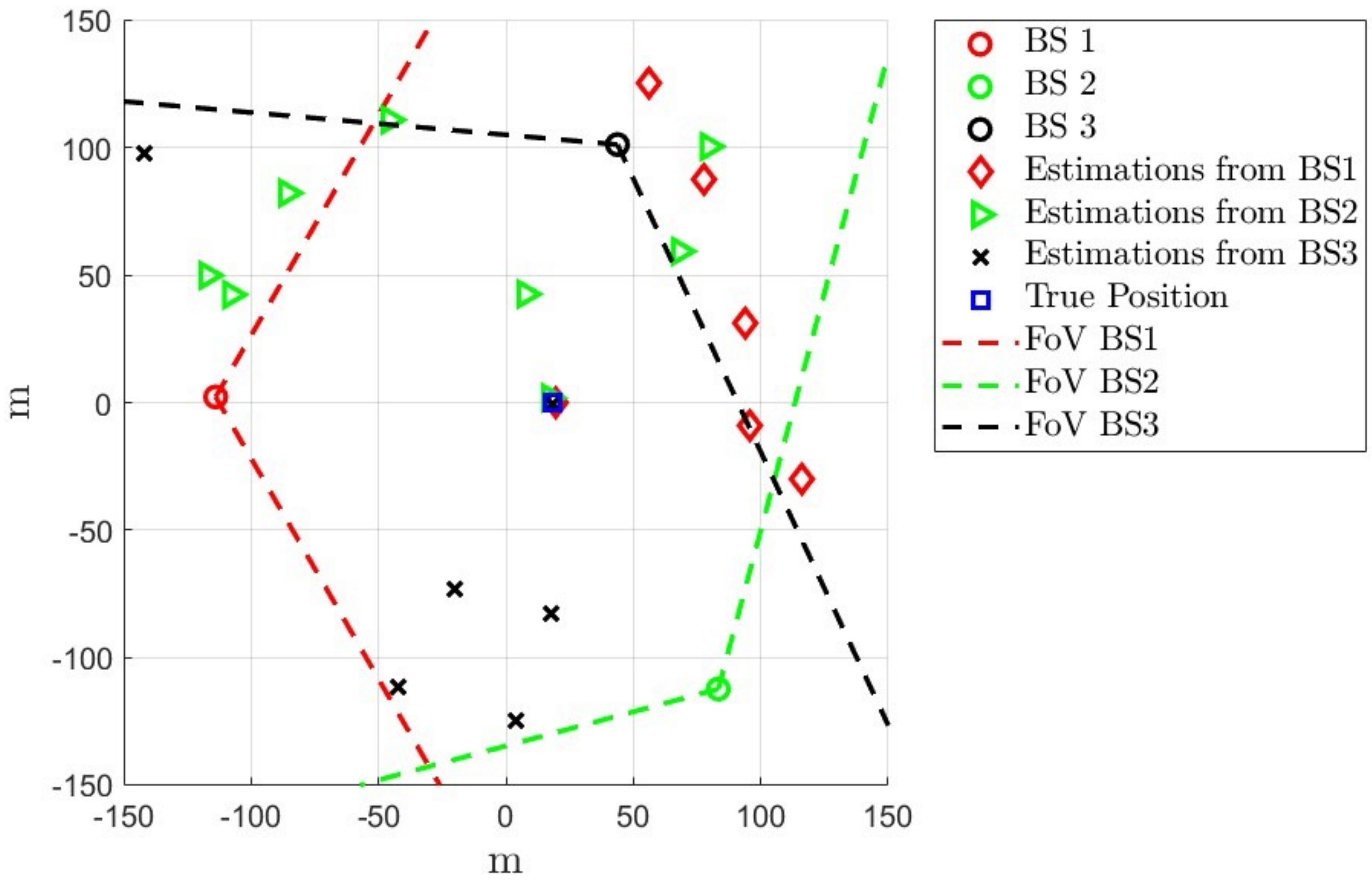


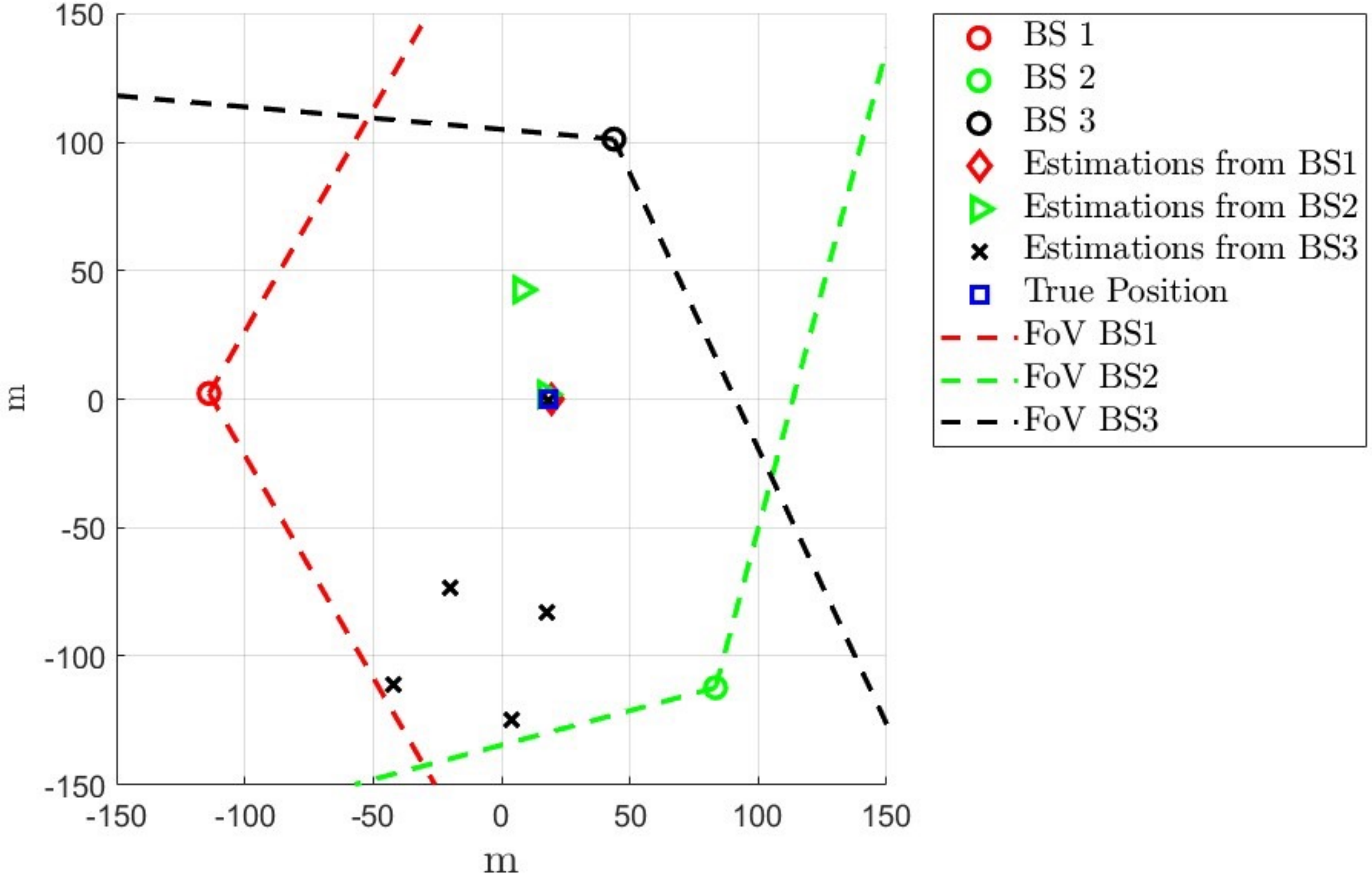
Figure 7: Scenario for the simulations. Vincent Square, London, is used.

Beamforming Phase



- Each BS perform a beam scanning.
- At each AoA, the periodogram is compute.
- All the peaks above a threshold are sent to the CPU.
- The CPU map all the peaks to the absolute positions.

Pruning Phase



- The CPU removes all the peaks that are outside of the convex hull.

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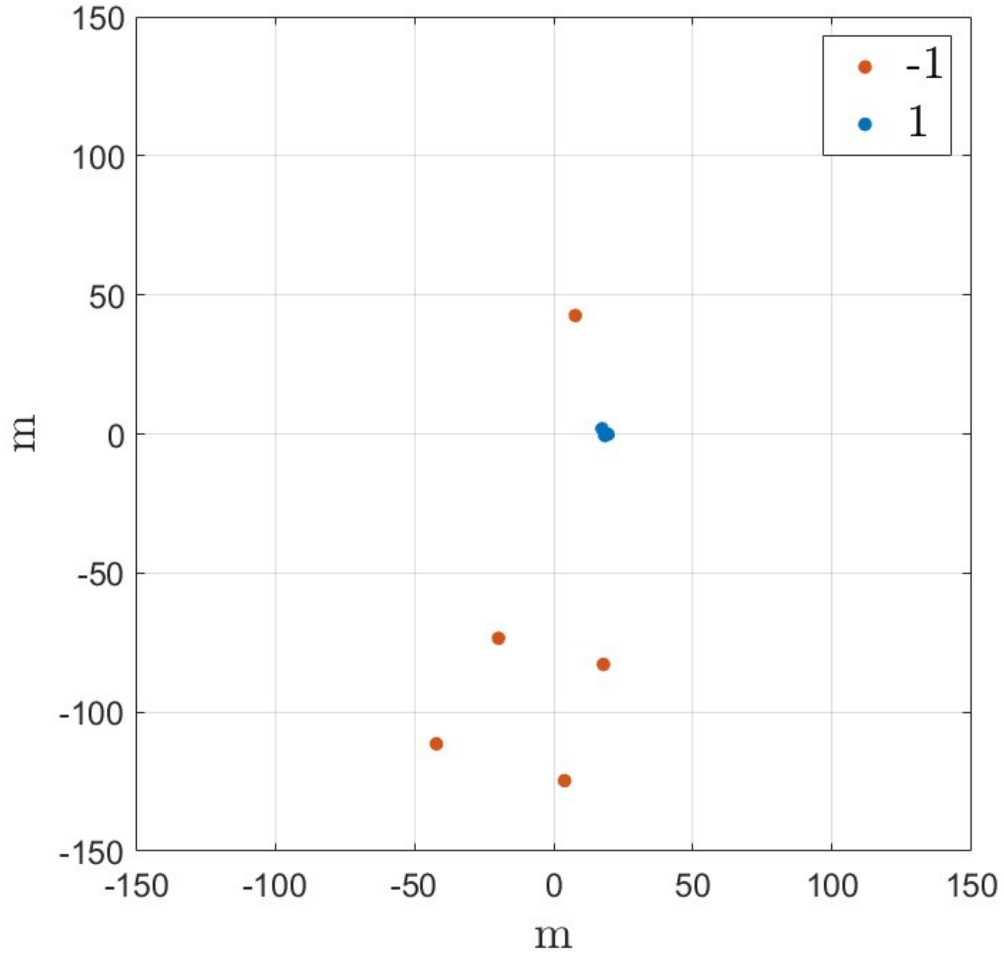
Classification Phase



- The CPU uses DBSCAN in order to classify the peaks.
- The cluster are defined as a set of 3 points.
- The separation of the peaks is up to 5 m
- DBSCAN gives the number of targets and the clusters.

Future work and open questions

- How can we combine the estimates of AoA and ToA in order to enhance the estimation accuracy?

- How fast the beam scanning phase needs to be so that all BSs can see the same target in the same position?

- Will these approach work for multiple object detection?

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Vielen Dank
für Ihre Aufmerksamkeit