FORSCHUNGSINITIATIVE
KO-FAS

Transponder Based Angle of Arrival Estimation

Transponderbasierte Winkelschätzung

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Outline

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- Ko-TAG overview
- Angle of Arrival (AoA) principle
- System overview and realisation
- Performance

Ko-TAG Overview

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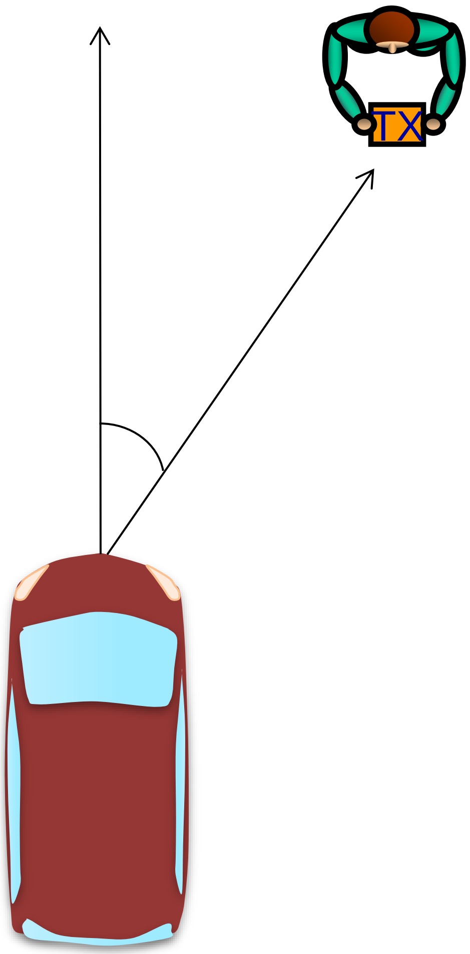
- Recognition and exclusion of hazards due to tracking and motion detection of the vulnerable road user
- Reducing fatal accidents by recognition of vulnerable road users (VRU) even in blocked line of sight conditions
- Increase car2car safety especially at intersections
- Methods for tracking:
  - Angle of arrival (AoA) measurement
  - Distance measurement
- Uses 5.8 GHz band
- INS for motion detection
- Full integration of the components

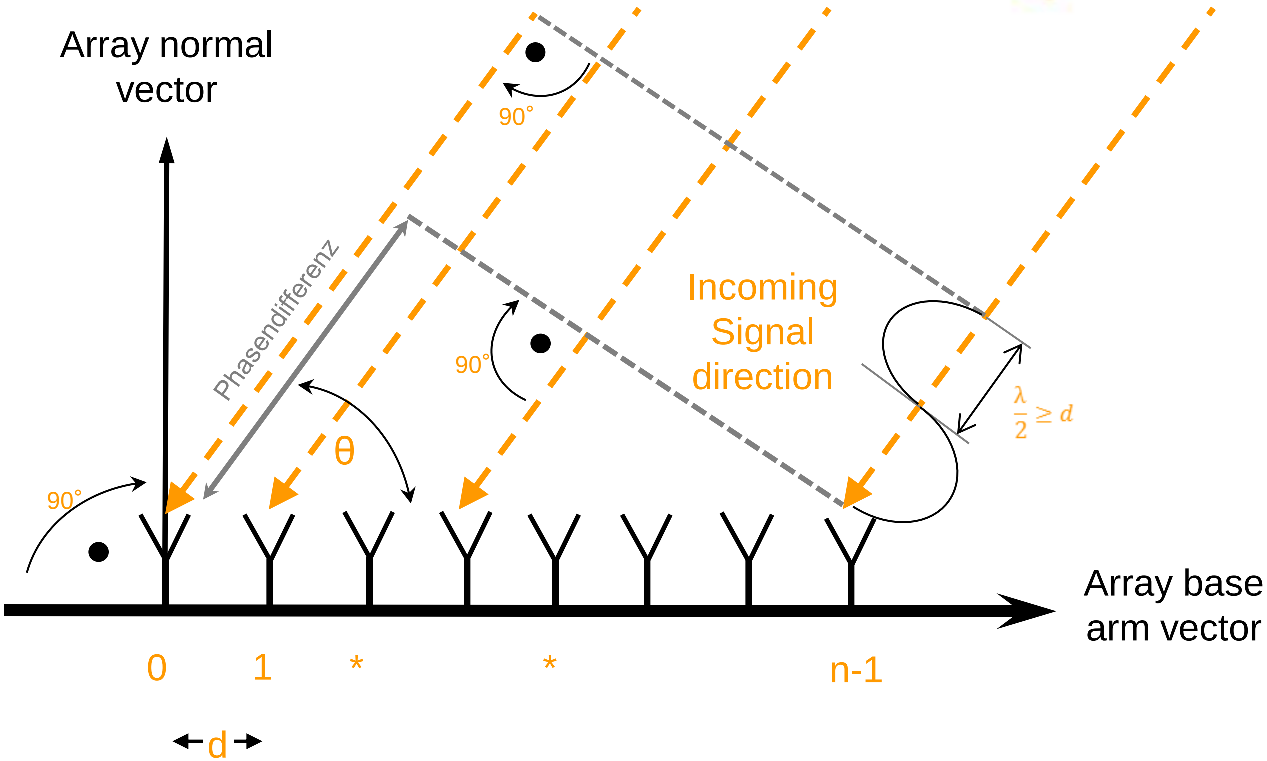


Ko-TAG Overview

- High Accuracy
- Timely detection of VRUs due to high received signal power
- Target classification through active response
- Detection of Angle of Arrival (AoA) in non-line-of-sight situations
- Fusion with cooperative ranging and inertial sensors (INS)
  - Simple concept for accurate positioning
  - Estimation and prediction of position of a VRU

Angle of Arrival Basics

- Propagation of the signal as plane wave in the far-field
- Difference of propagation delay measured as phase shift of the signal between antenna elements
- Narrowband constraint (bandwidth << carrier frequency)
- Distance d ≤ λ/2 between Antenna elements resolves ambiguity



AoA estimation Algorithms Overview

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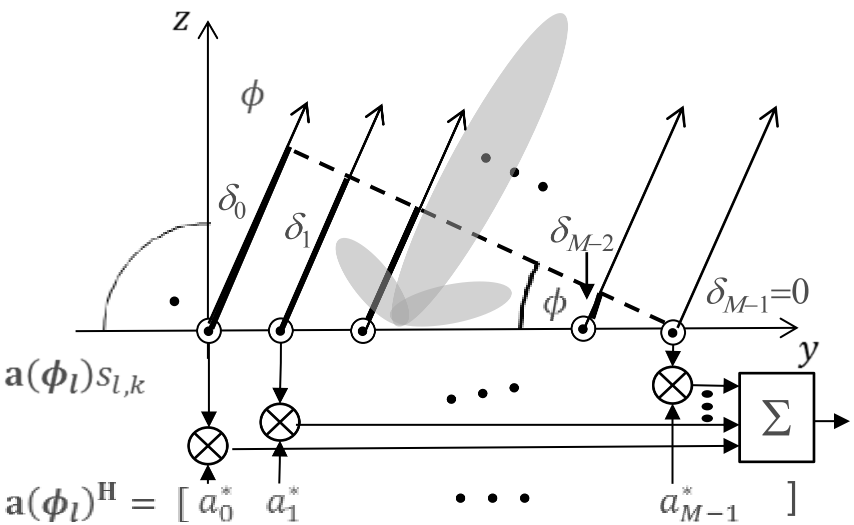
- Classical approaches
  - Beamforming approach (maximum- or zero-steering)
  - Capon‘s Minimum Variance approach
- Classical beamforming methods use little structural information
- Subspace based methods to achieve high resolution/accuracy
  - MUSIC, Root MUSIC, Cyclic MUSIC
  - ESPRIT, Unitary ESPRIT
- Enhancement of multipath separation through
  - Spatial smoothing (*Forward-Backward Spatial Smoothing*)
  - Sequential and iterative estimation approaches

Comparison Beamforming/MUSIC

Beamforming



- Steering the listening beam with *steering vector* **a** equivalent to transmitting in direction $\boldsymbol{\phi}_l$

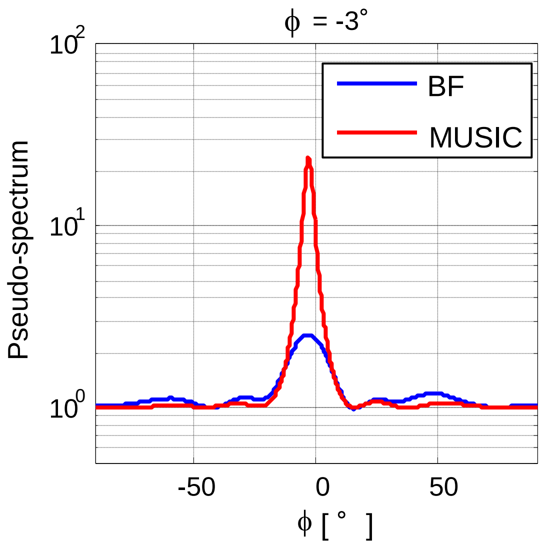
MUltiple SIgnal Classification

- Allows super-resolution
- Compute covariance matrix

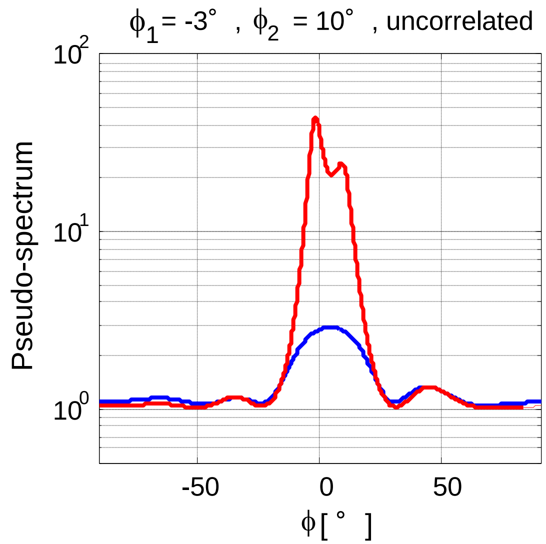
$$\mathbf{R}_{\mathbf{uu}} = \sum_{k=0}^{K-1} \mathbf{u}_k \mathbf{u}_k^H$$

- Structural matrix analysis (Eigenvalue decomposition) separates noise and signal modes
- Search for $\boldsymbol{\phi}_l$ with minimal correlation between noise modes and steering vector **a**

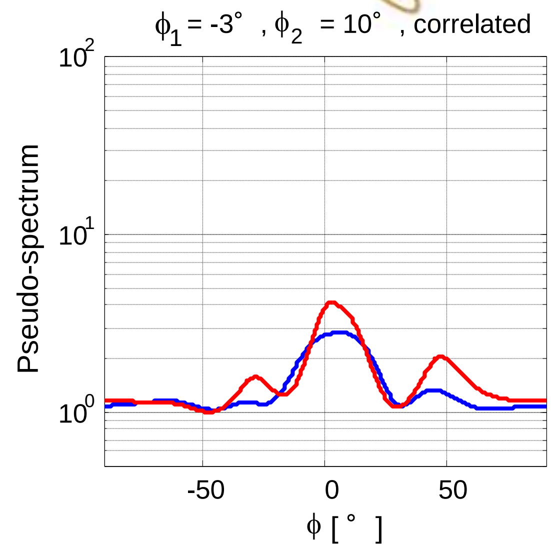
Comparison Beamforming/MUSIC



BF	-3°
MUSIC	-2.8°



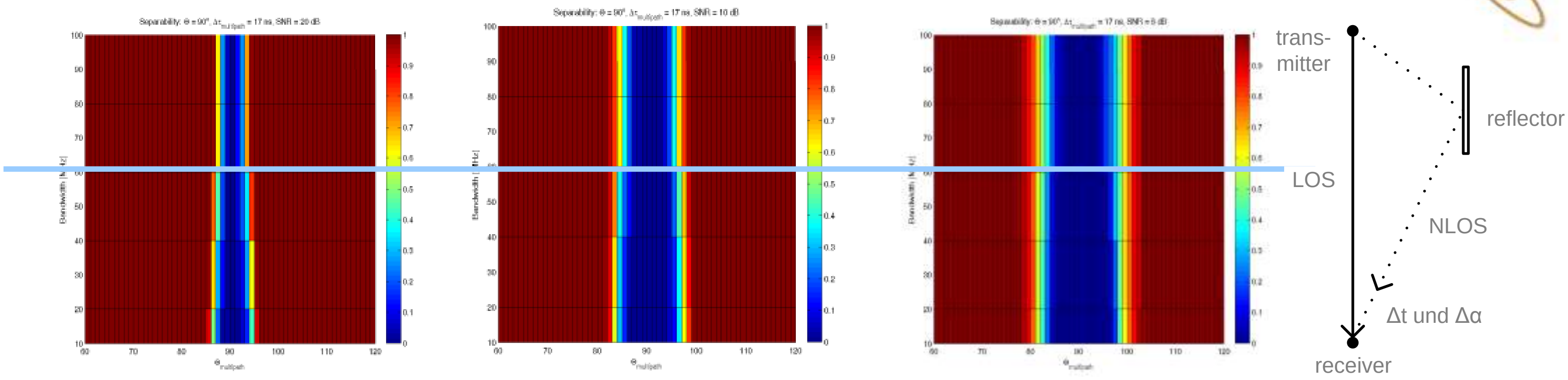
BF	5°	44°
MUSIC	-1.6°	9°



BF	6.8°	44°
MUSIC	3°	47.6°

- Estimators result in different angle estimates
- MUSIC yields sharper maxima than Beamforming (BF) and usually more accurate results
- Correlated signals (e.g. multipath with $\tau < 1/B$) especially critical

Separability

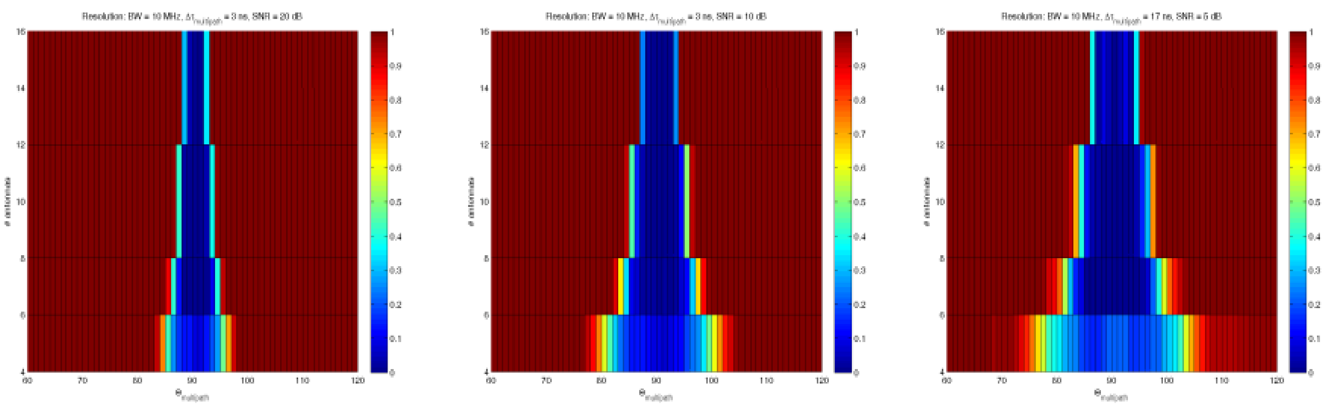


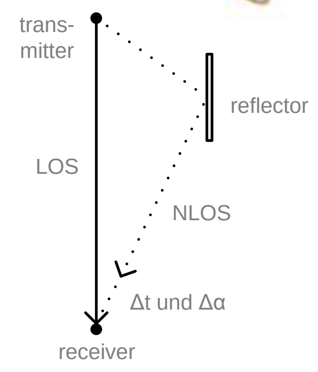
- Main path 90°, 6 Antenna elements Δt = 17 ns
- Mostly SNR influence

  10 MHz, => (20 dB|± 5°),(10 dB|±7°),(3 dB|±10°)

  100 MHz, => (20 dB|± 3°),(10 dB|±4°),(3 dB|±8°)
- Little gain through increased bandwidth

Separability



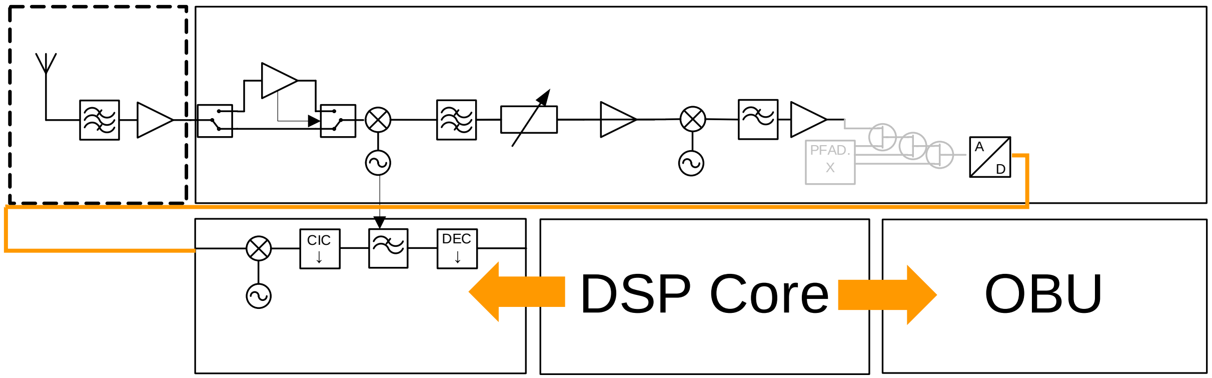


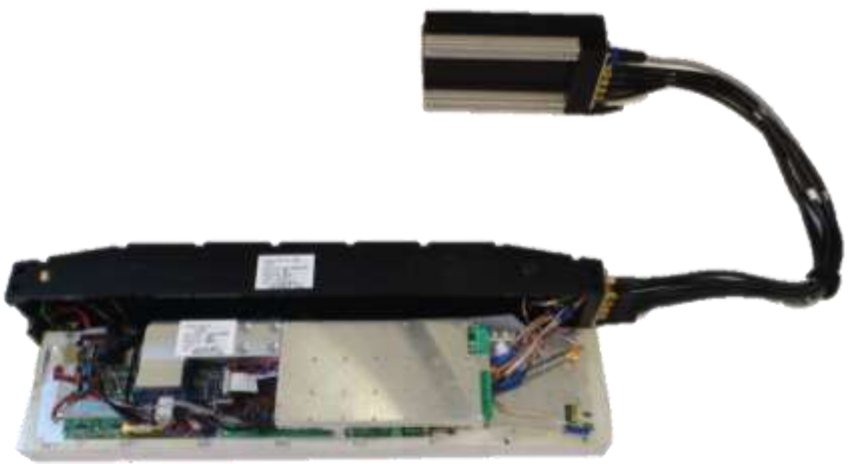
- Main path 90° , Δt = 3 ns
- Mostly SNR influence

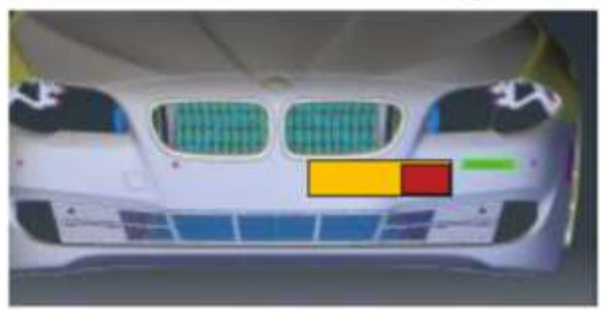
  4 Antenna elements=> (20 dB|± 6°),(10 dB|±10°),(3 dB|±15°)

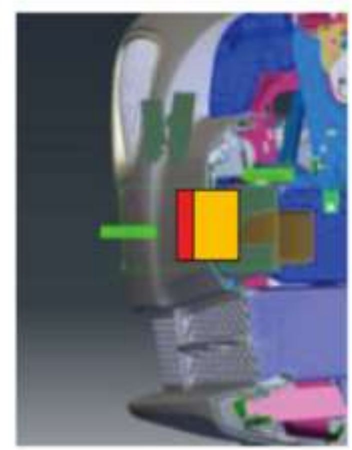
  16 Antenna elements=> (20 dB|± 3°),(10 dB|±4°),(3 dB|±6°)
- Large gain through more antenna elements

System Architecture



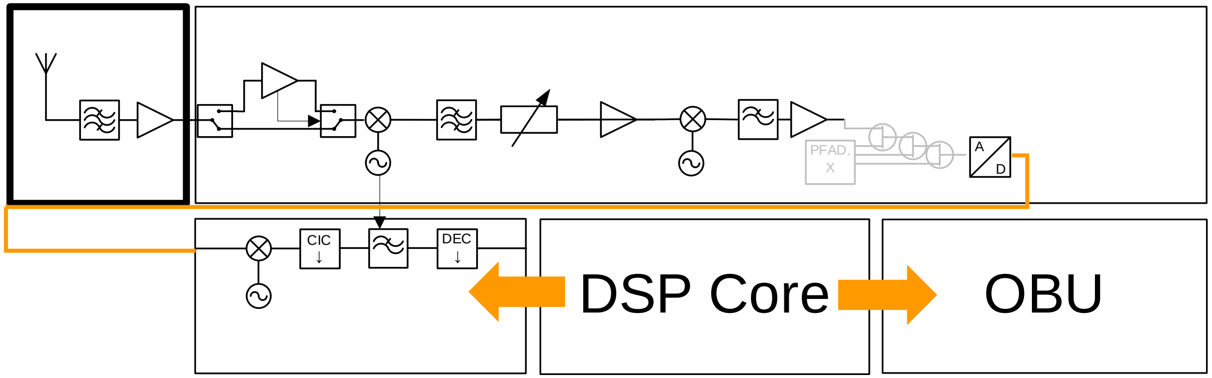


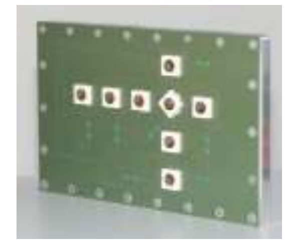


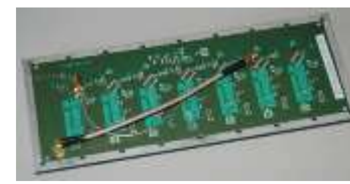


Onboard Unit

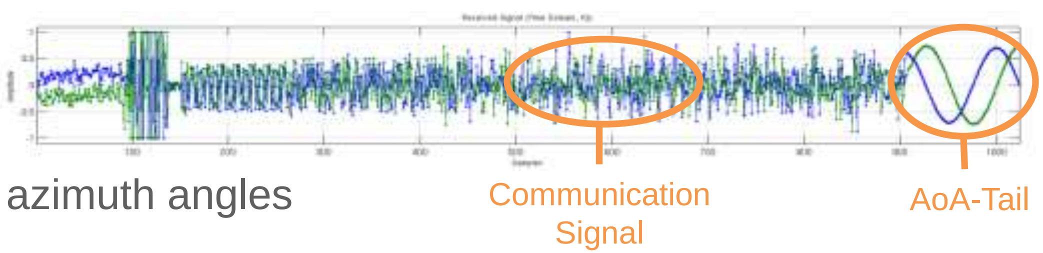
System Architecture – Antenna



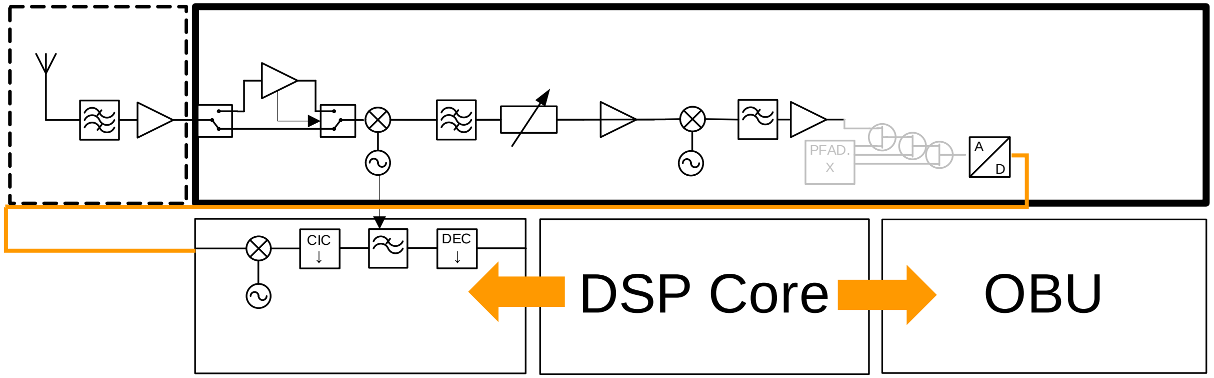


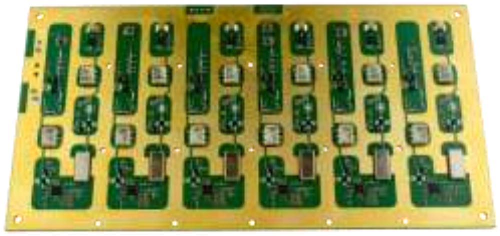


- Communications signal or AoA tail can be used for AoA measurement
- Antenna array with 6 elements for phase difference measurements
- 1D linear phased array
  - For better multipath separation
  - For higher angular resolution of azimuth angles
- 2D planar array
  - For azimuth and elevation estimation
  - High phase difference ⇔ polarisation dependency

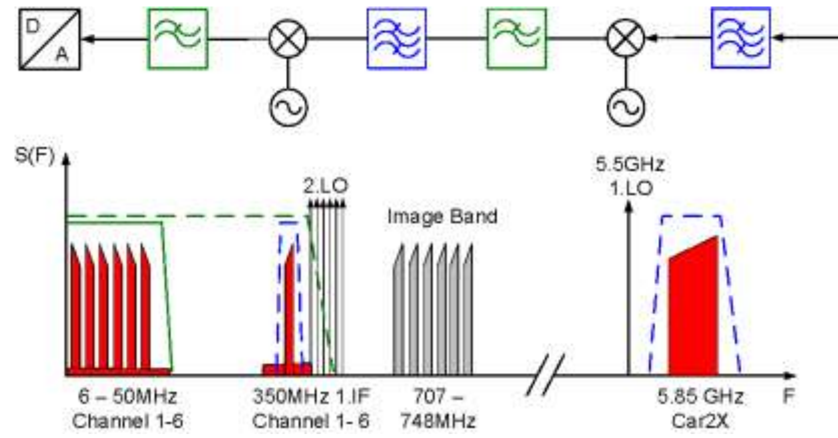


System Architecture – RF-Frontend

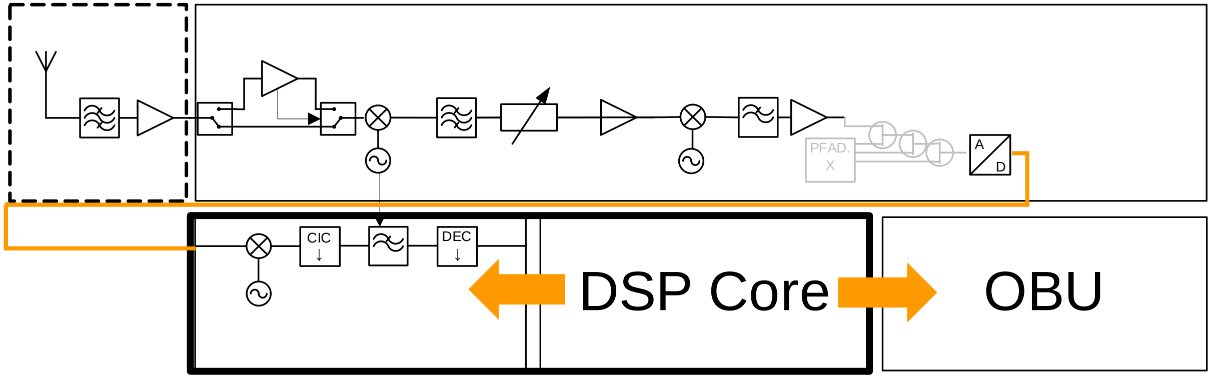




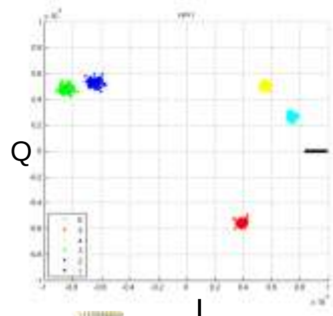
- Down conversion from 5.8 GHz to 6 different intermediate frequencies
- Sampling with a single ADC with 104 Msamples/s
  - No jitter with no synchronisation
  - Simple digital design
  - Limited bandwidth 2–4 MHz
- Modular design with separate ADCs
  - Increased number of complete RX paths
  - Higher bandwidth possible
  - More demanding digital signal processing



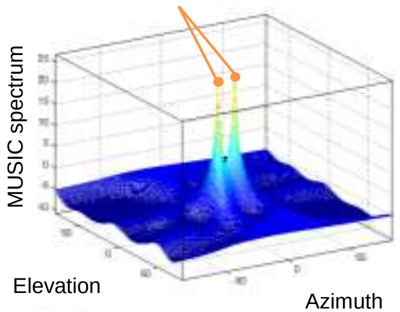
System Architecture – DSP Board



- Digital down-conversion (FPGA)
  - Down-conversion to IQ-baseband
  - Sampling rate decimation
  - Preprocessing
- AoA Estimation (DSP)
  - External signal detection => waveform independent
  - Due to high performance platform either high update rate or higher resolution possible

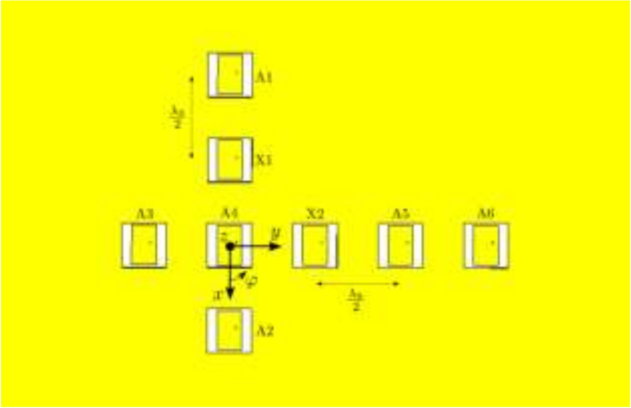


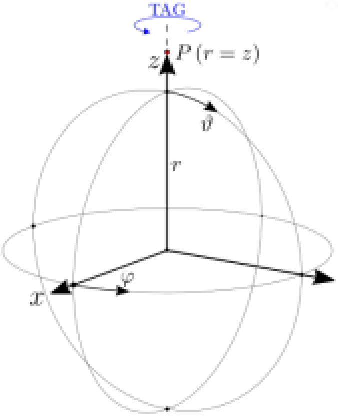
Estimated angles in the MUSIC spectrum



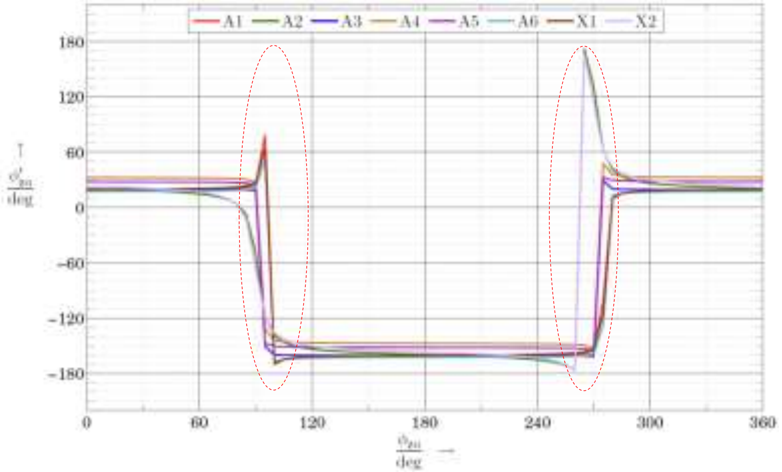
Performance – Antenna
Cross arrangement of 8 Elements

Element arrangement + rotating transponder position





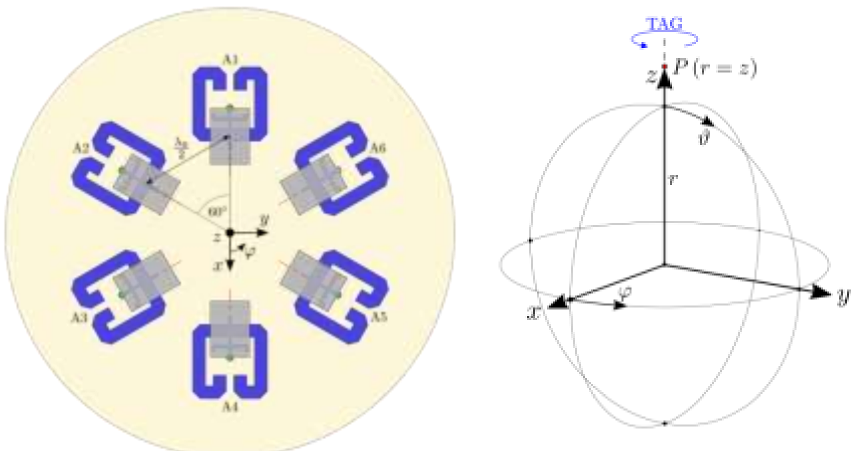
Phases of single antenna elements (zenith)



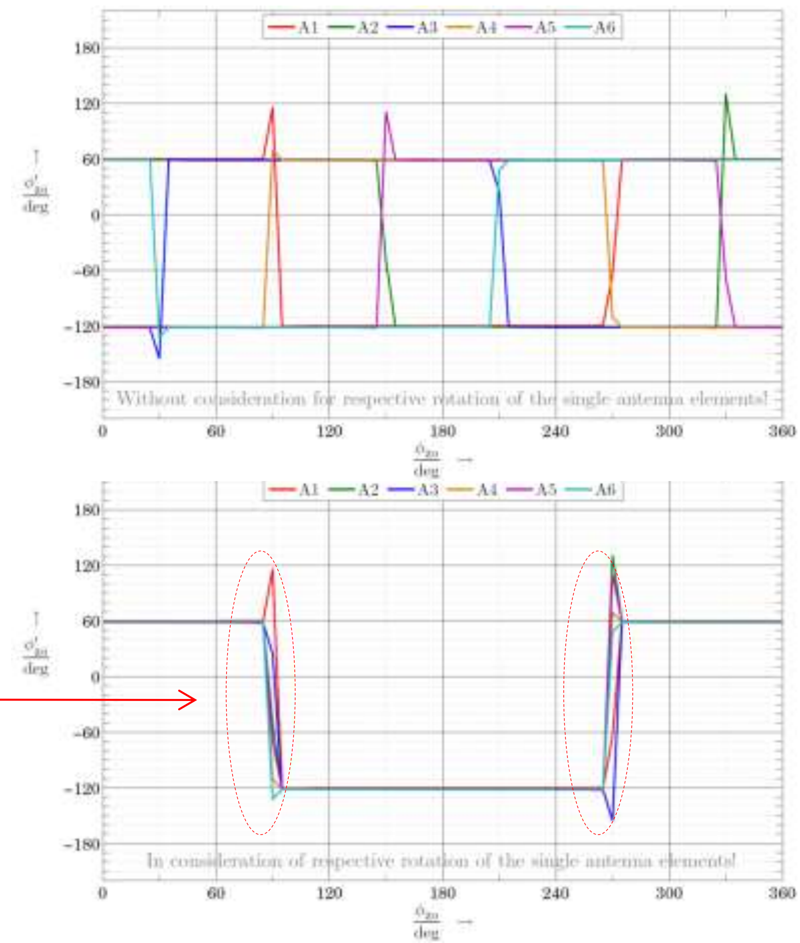
- Six active and two passive antenna elements
- Mostly parallel phases
- Not congruent phases and in case of orthogonal polarization between transponder and single antenna

Performance – Antenna
Axisymmetric arrangement of six elements

Element arrangement + rotating transponder position

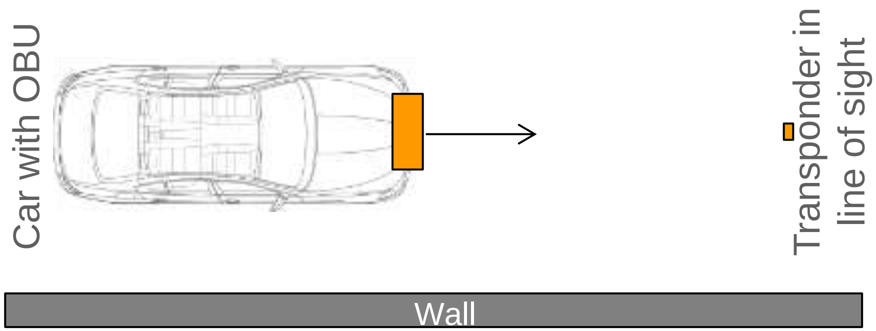


Phases of single antenna elements (zenith)

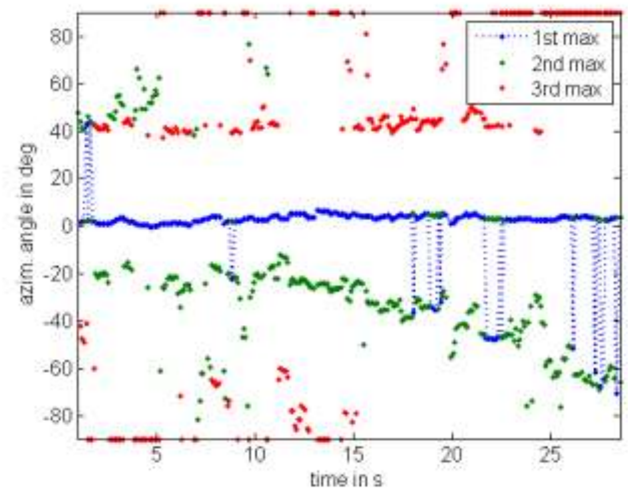


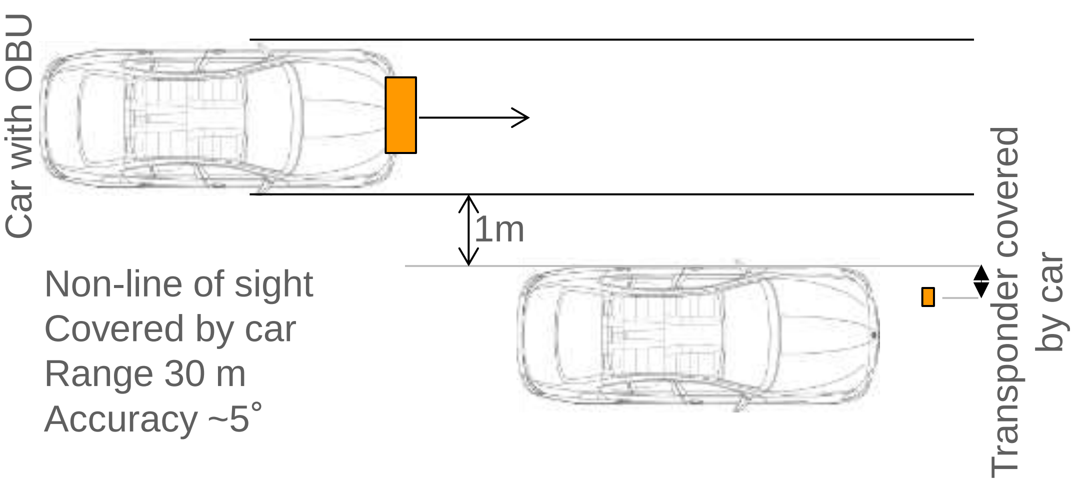
- Absolute parallel phases (congruent)
- Orthogonal polarization between transponder and antenna → blind sector
- At the most only two elements are effected in this case of this arrangement

Performance System

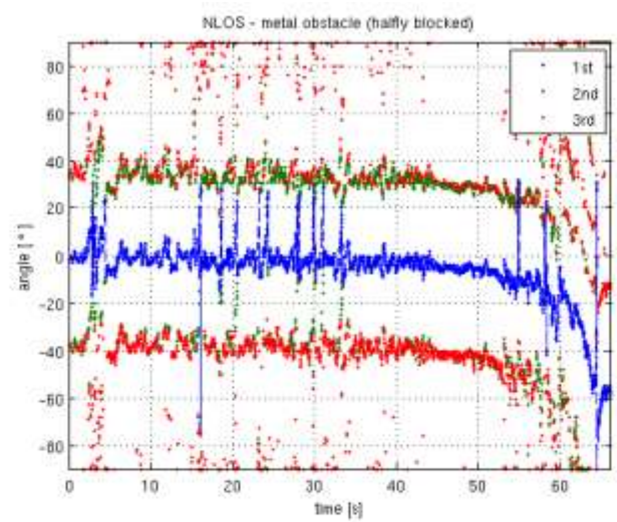


Line of sight – limited multipath propagation
Seperatable reflection on side wall
Range up to 200m
Accuracy ~1°





Non-line of sight
Covered by car
Range 30 m
Accuracy ~5°



Conclusion

- 5.8 GHz system for locating VRUs
- 2D Antennas for detection of special situations
  - Cross arrangement of antenna elements
  - Axis-symmetric arrangement of antenna elements
- High Performance AoA estimation
  - MUSIC Based with FB spatial smoothing
  - ~1000 estimations per second possible
  - High separability of multipath propagation
- Localisation even in non line-of-sight conditions
- Localisation unit integrated in front-bumper

Thank you for your attention!

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