The Intelligent Radar Signal

by Christian Sturm and Werner Wiesbeck

Universität Karlsruhe (TH)
Research University • founded 1825

Institut für Höchstfrequenztechnik
und Elektronik

IHE

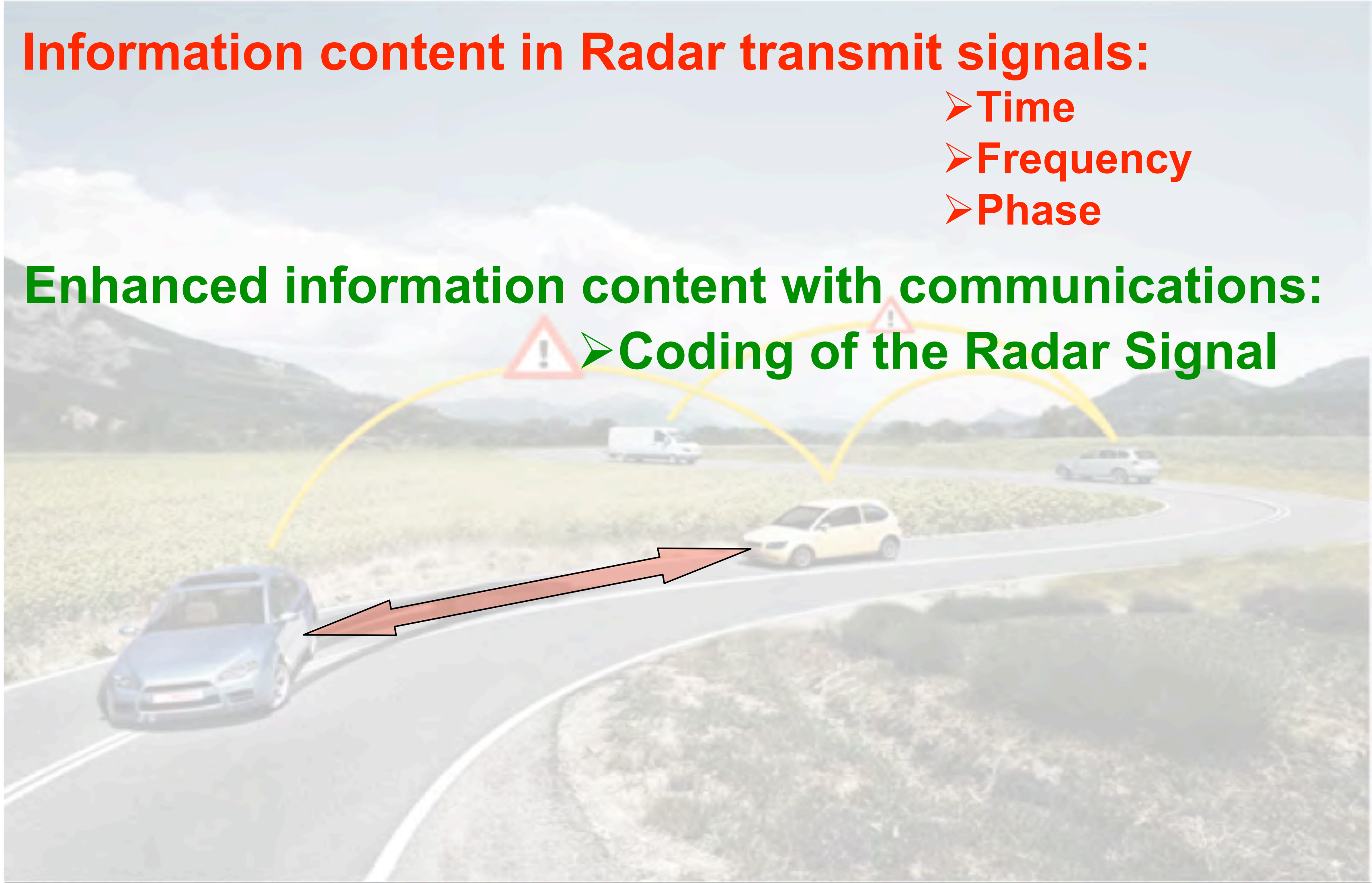
Enhancement of the Radar Signal Information Content

Information content in Radar transmit signals:

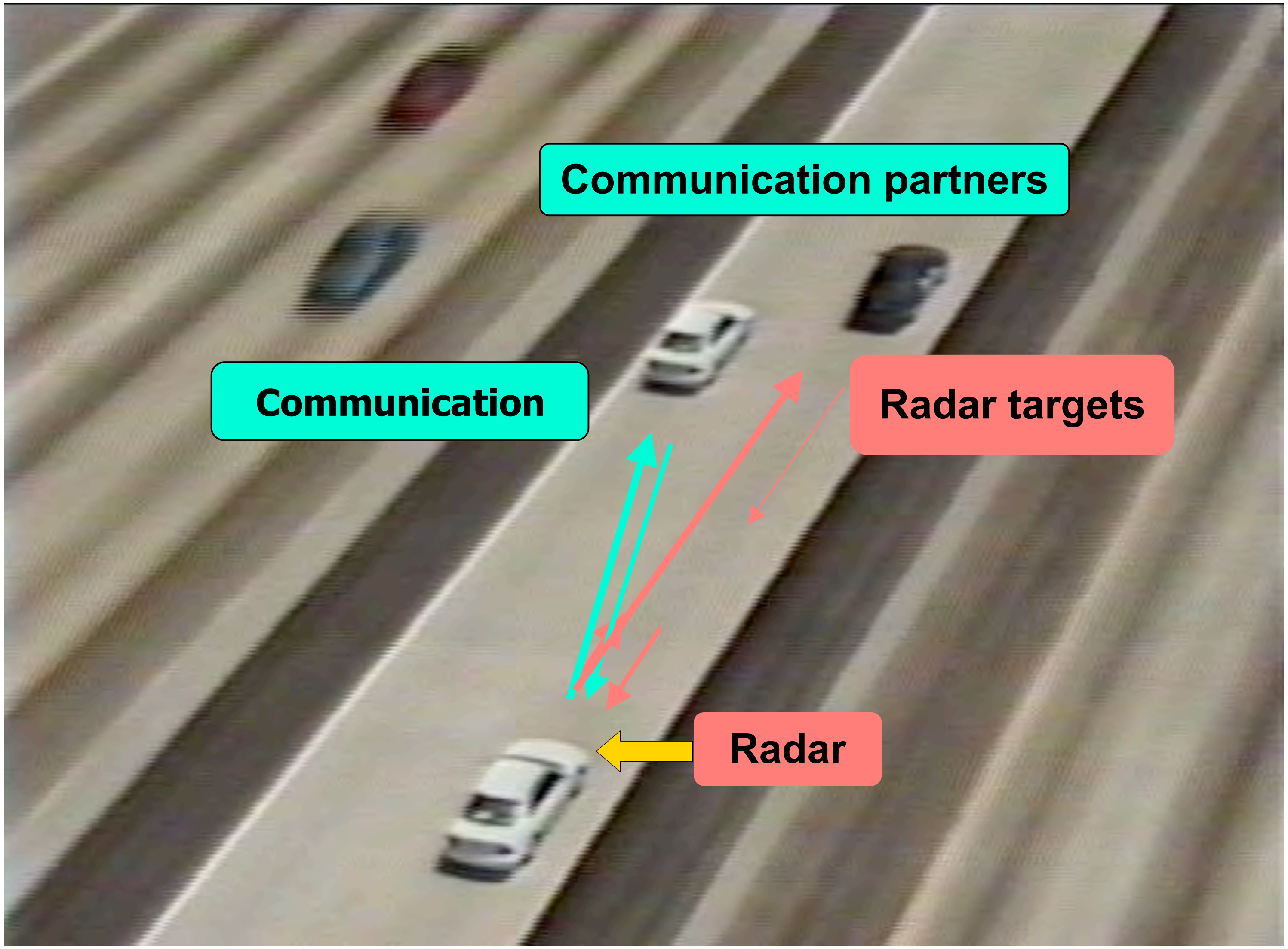
- Time
- Frequency
- Phase

Enhanced information content with communications:

- Coding of the Radar Signal



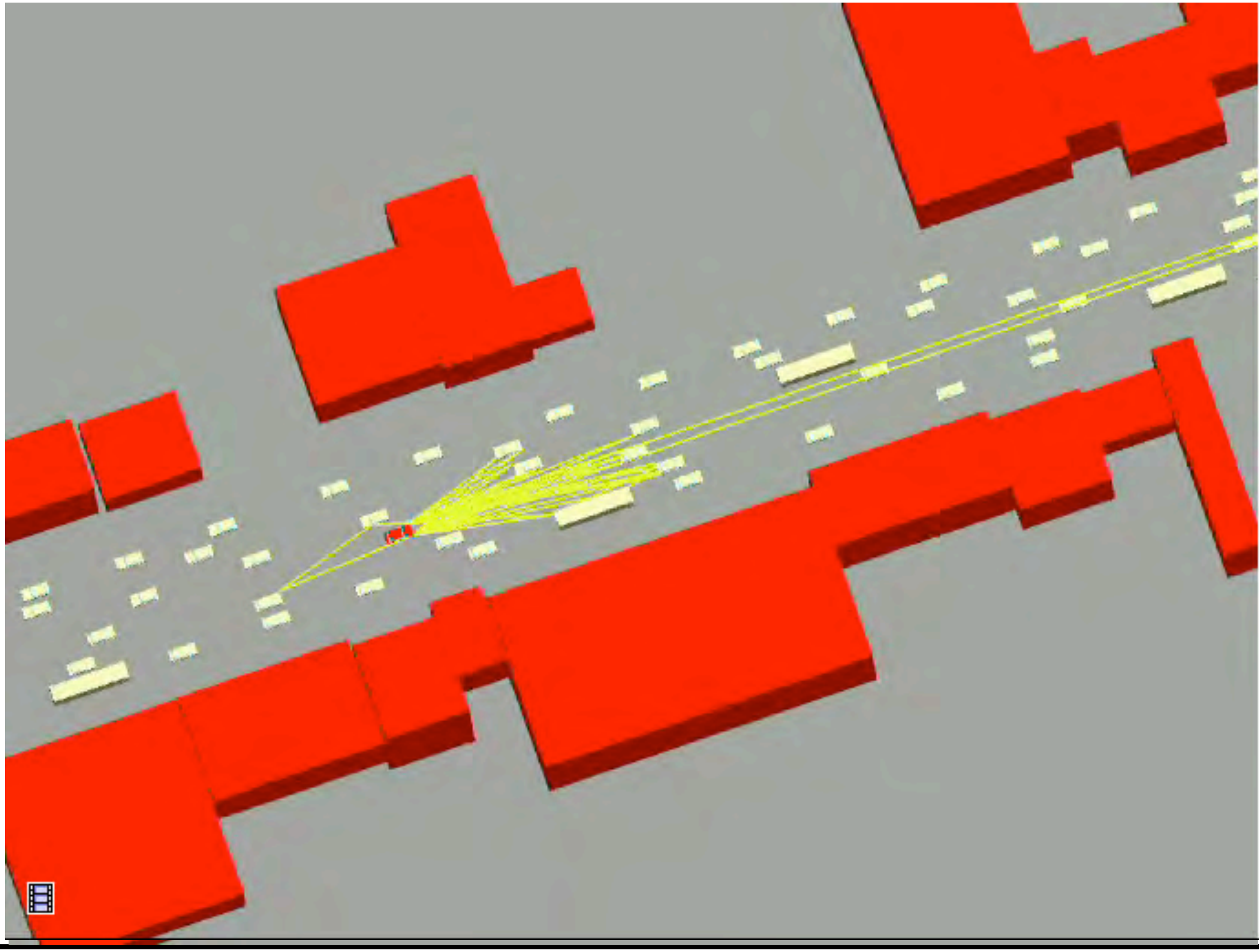
Motivation – Basic Idea



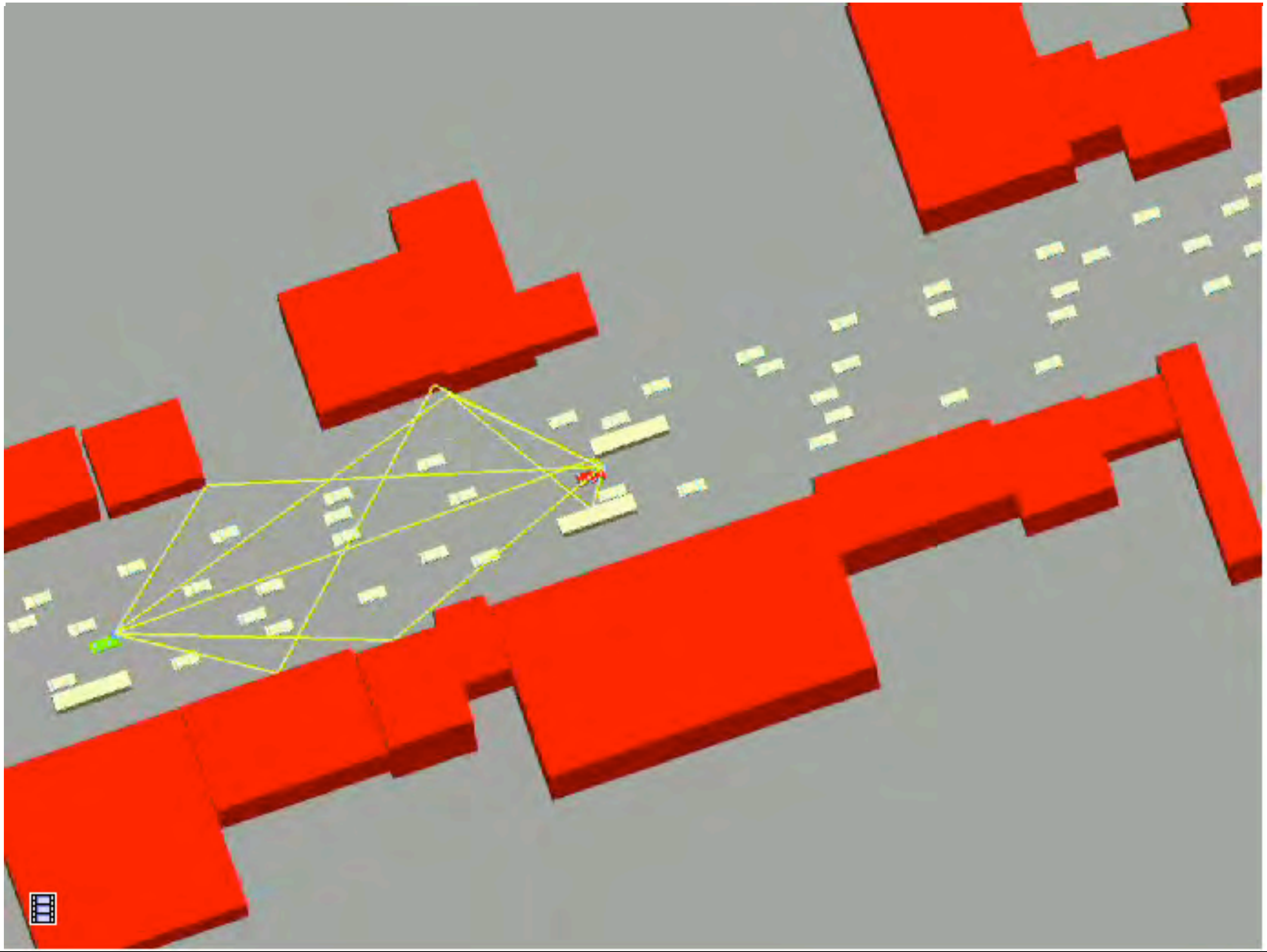
Universität Karlsruhe (TH)
Research University • founded 1825

Institut für Höchstfrequenztechnik
und Elektronik
IHE

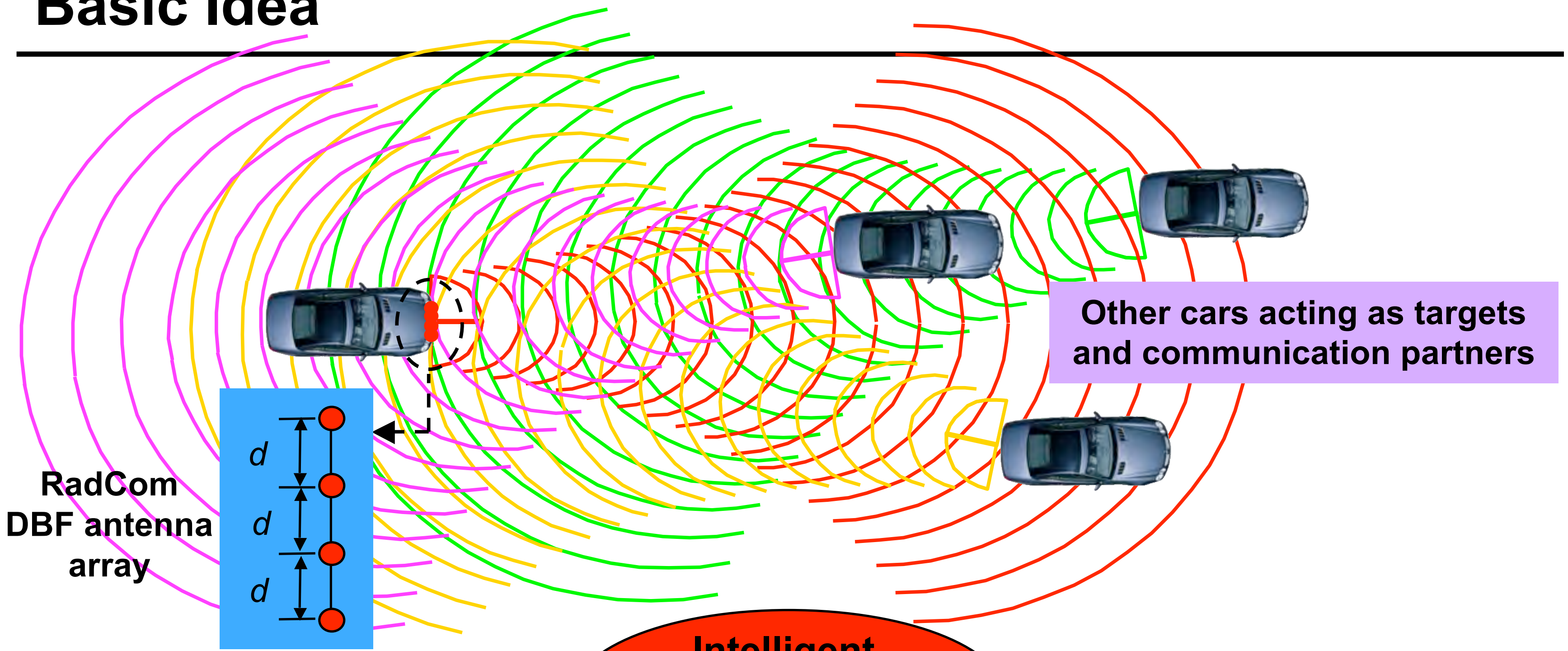
Radar and Communication in Traffic



Radar and Communication in Traffic



Basic Idea



Intelligent Transportation System (ITS)

2D Radar Imaging
- by digital beam-forming
- range, speed azimuth

Communications
- MIMO
- Diversity

- Driver Assistance
- Congestion Avoidance
- Dynamic Route Planning
- PreCrash Detection

Radar Information and Communication Objectives

Basic information: range+speed

$$R = \frac{2\Delta t}{c_0}$$

$$f_D = \frac{2v_r}{\lambda}$$

Bandwidth: range resolution

$$\Delta R = \frac{c_0}{2B}$$

Receive power P_{Rx}: ~1/R^4

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} \sigma \lambda^2}{(4\pi)^3 R^4}$$

Signal duration depending on:

- **Radar powe budget**
- **desired Doppler resolution**

Objective:

Coding of the transmit signal to include information

Possible Radar Problems:

- **Influence on:**
  - **range resolution/accuracy**
  - **velocity resolution/acc.**
  - **maximum range**
- **interferences**
- **beam-forming algorithms**

Coding of Radar Signals

Well known Radar coding for EW purposes:

- Staggering
- Puls position modulation (PPM)
- Phase coding
- Frequency hopping
- ......

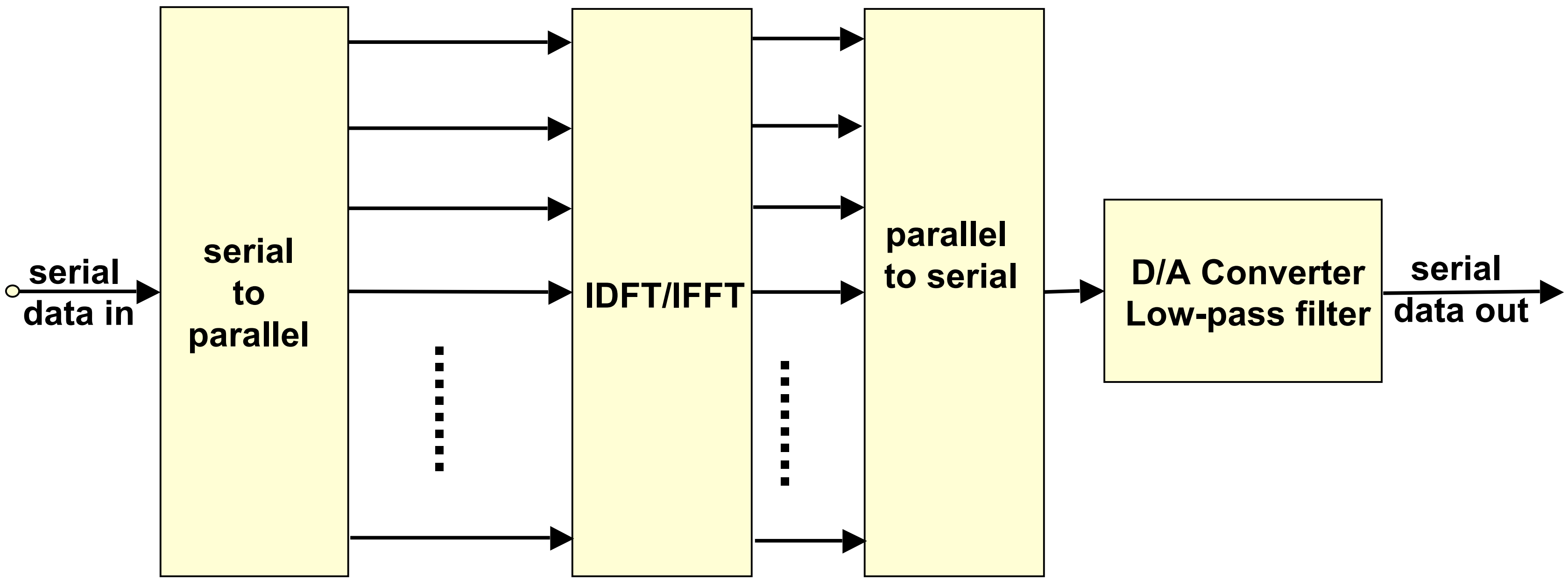
Coding in communications:

- DPSK, QPSK, M-PSK
- OFDM
- CDMA
- ......

OFDM

OFDM Multi Carrier Transmitter Scheme

Orthogonal(FDM) scheme as a digital multi-carrier method



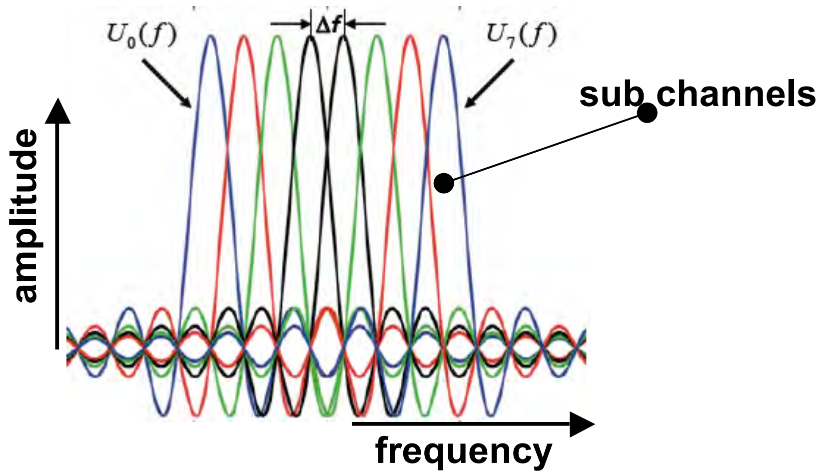
Dividing data into parallel data streams

Each sub-carrier is modulated at a low symbol rate

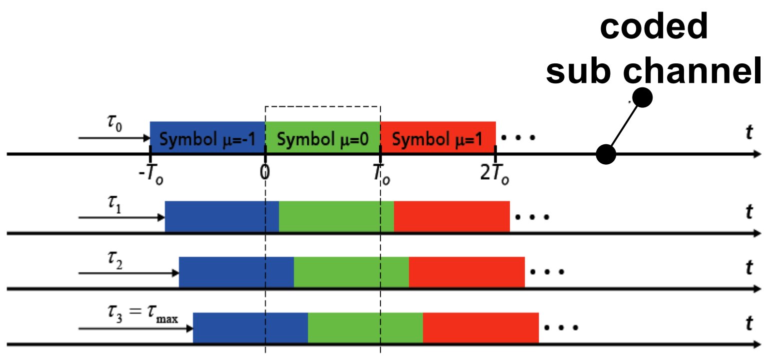
Total data rates similar to single-carrier schemes

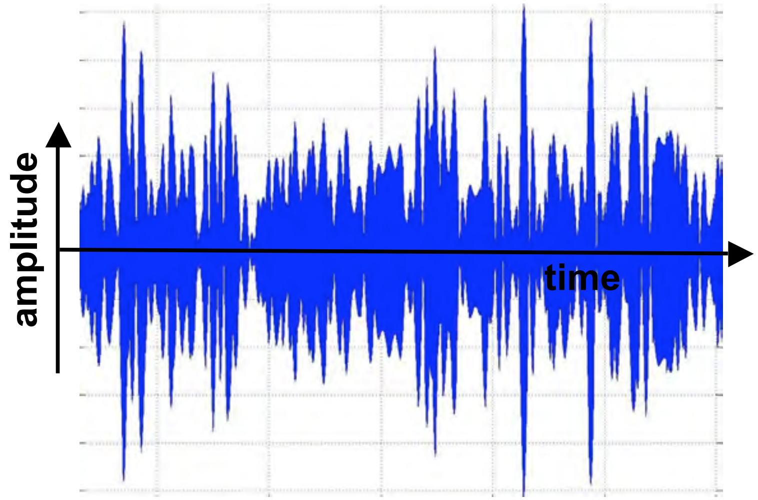
OFDM Characteristics

Frequency Domain



Multi-path in Time Domain



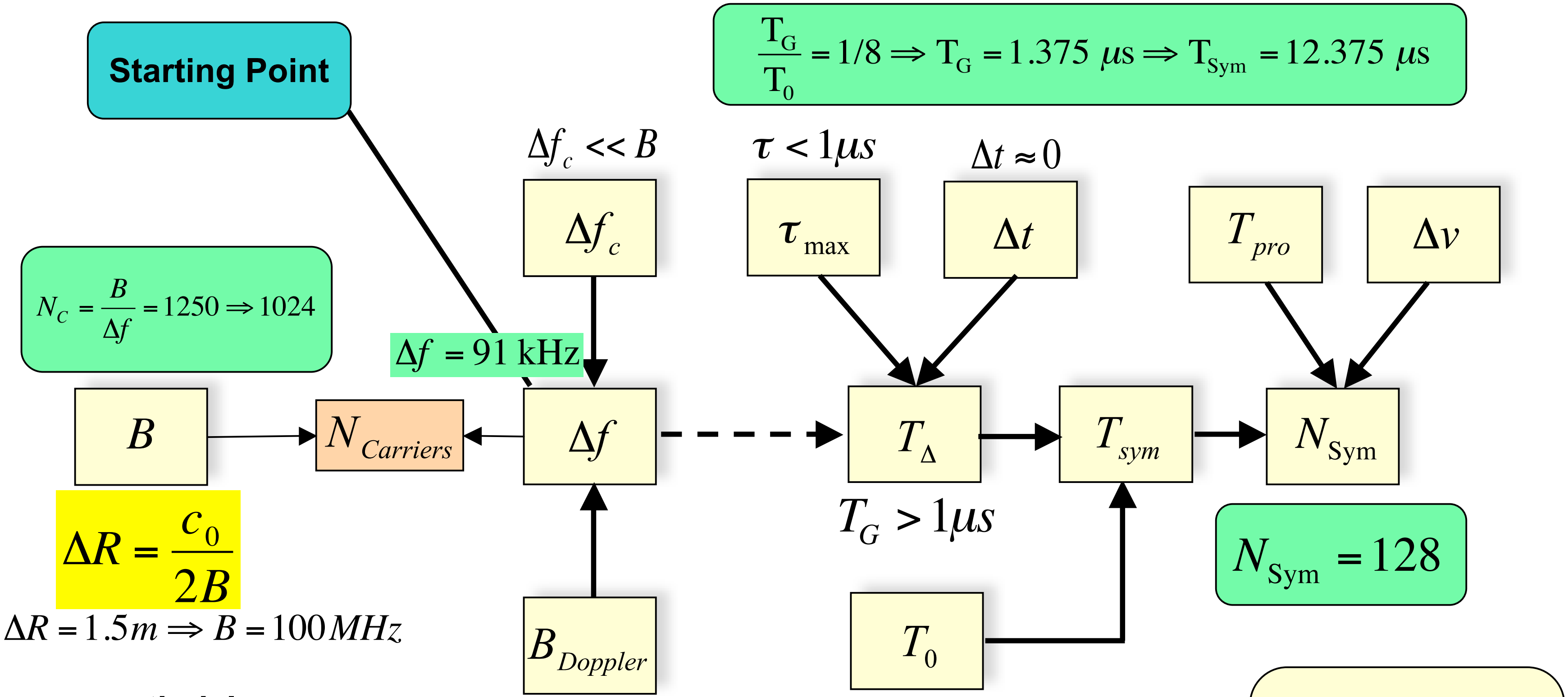


OFDM Advantages / Disadvantages

- **Advantages:** Hardware Integration
  - efficiency (FFT/IFFT)
  - robustness against ISI (cyclic prefix)
  - low sensitivity to time synchronization errors

- **Disadvantages:**
  - Doppler shift and Doppler spread sensitivity
  - frequency synchronization problems
  - high peak-to-average-power ratio (PAPR)

Radar-Communication System Design



$\Delta f > 10 f_{D\max}$

$f_0 = 24$ GHz
$v_{r\max} = 50$ m/s

$$f_D = \frac{2v_r}{\lambda} \Rightarrow \Delta f > 80 \text{ kHz}$$

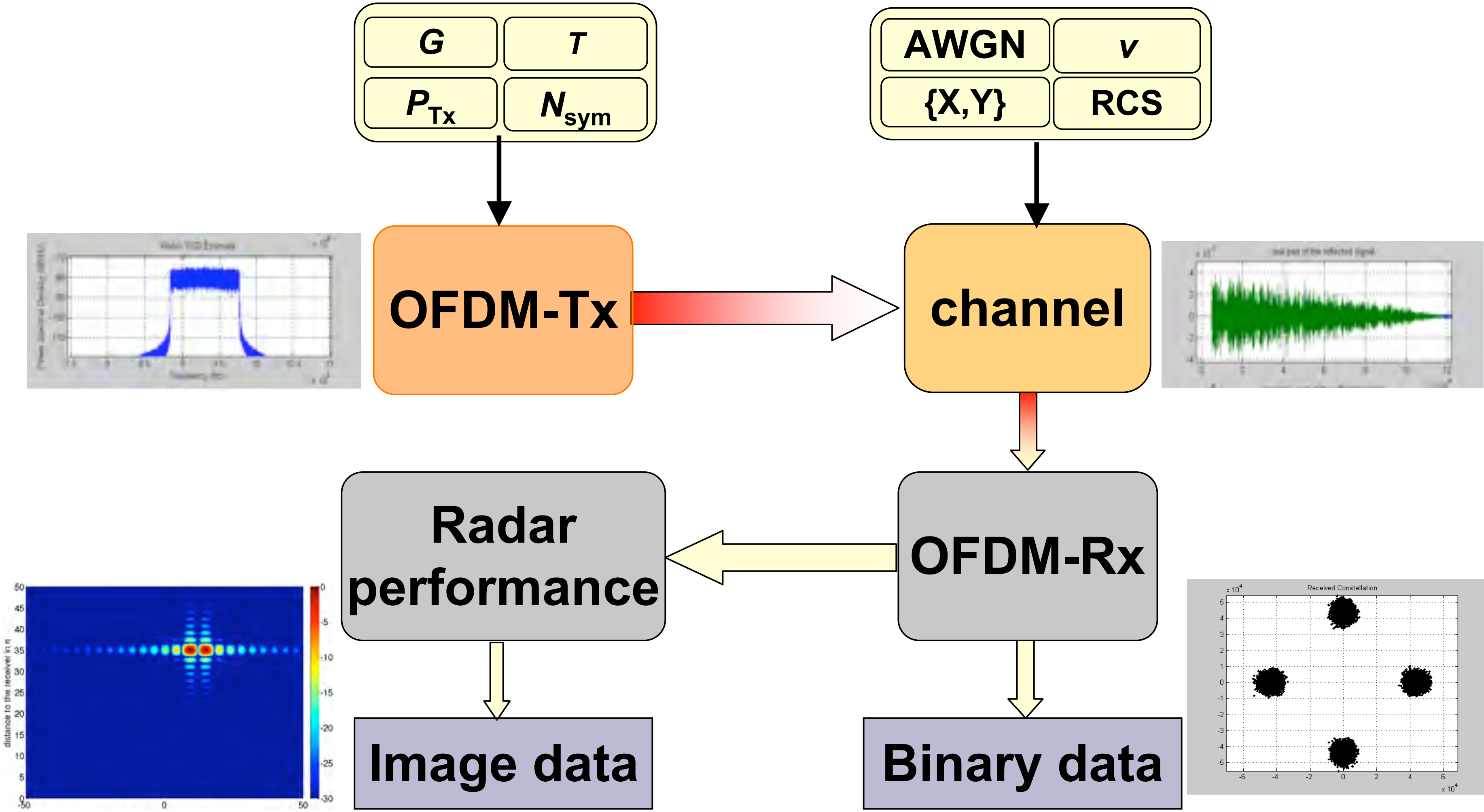
$$T_0 < 12.5\ \mu s \Rightarrow T_0 = 11\ \mu s$$

Unambiguous range

$$R_{Amb} = \frac{cT_0}{2} = 1650\ m$$

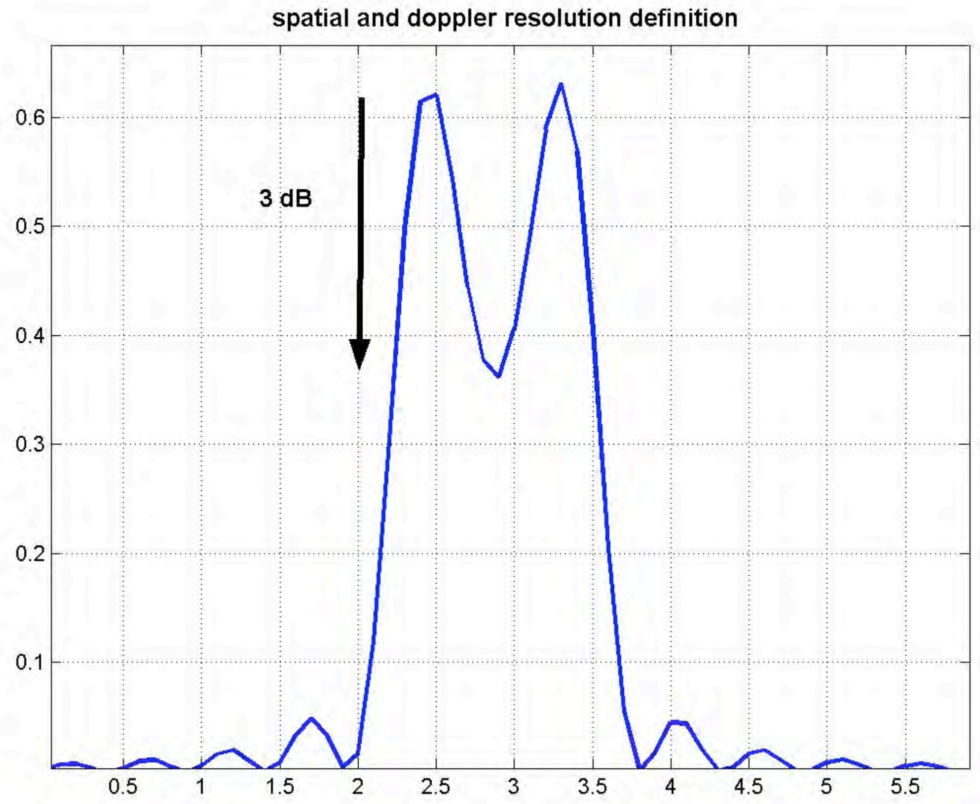
τ = path delay
Δv = Doppler resolution
f_0 = center frequency
Δf = carrier spacing
T_0 = OFDM period
T_G = guard interval
T_{pro} = processing time

OFDM Coded Radar System Simulation



Definition of Resolution

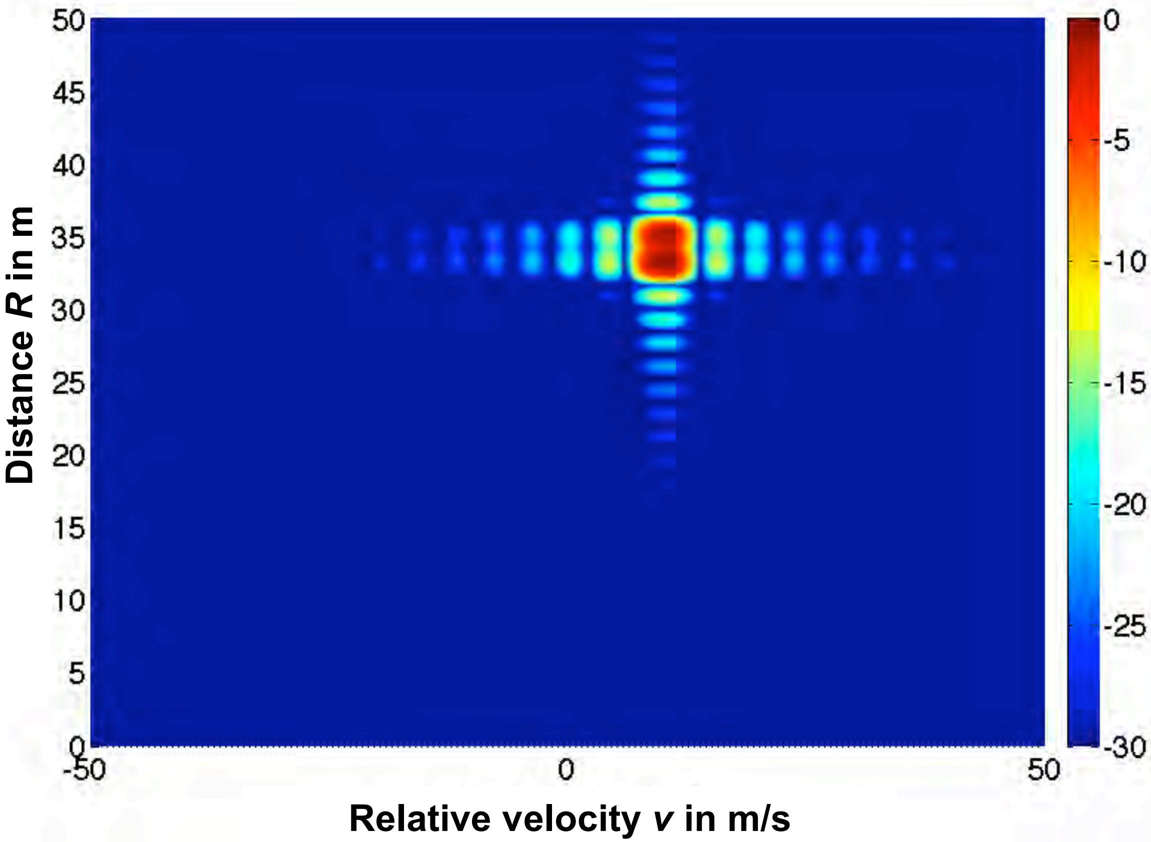
Example for 2 targets



Range Resolution Simulation for 2 Targets

$B \approx 93$ MHz

Target	Range *R* in m	Speed *v* in m/s
z_1	33,2m	35
z_2	10	10



$$\Delta R = \frac{c_0}{2B} = 1.61m$$

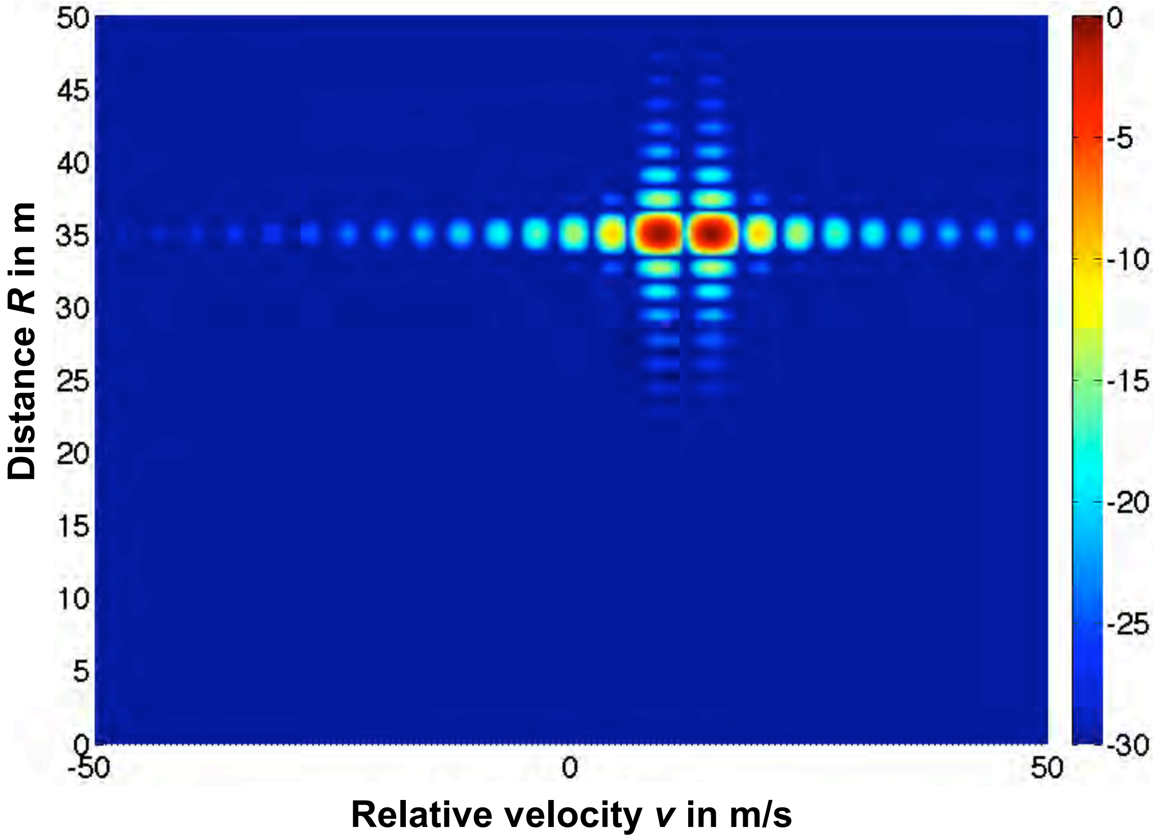
Simulation result :

$$\Delta R = 1{,}8m$$

Doppler Resolution Simulation for 2 Targets

T_{sym} = 12.375 µs
N_{sym} = 128

Target	Range *R* in m	Speed *v* in m/s
z_1	35	10
z_2	35	14

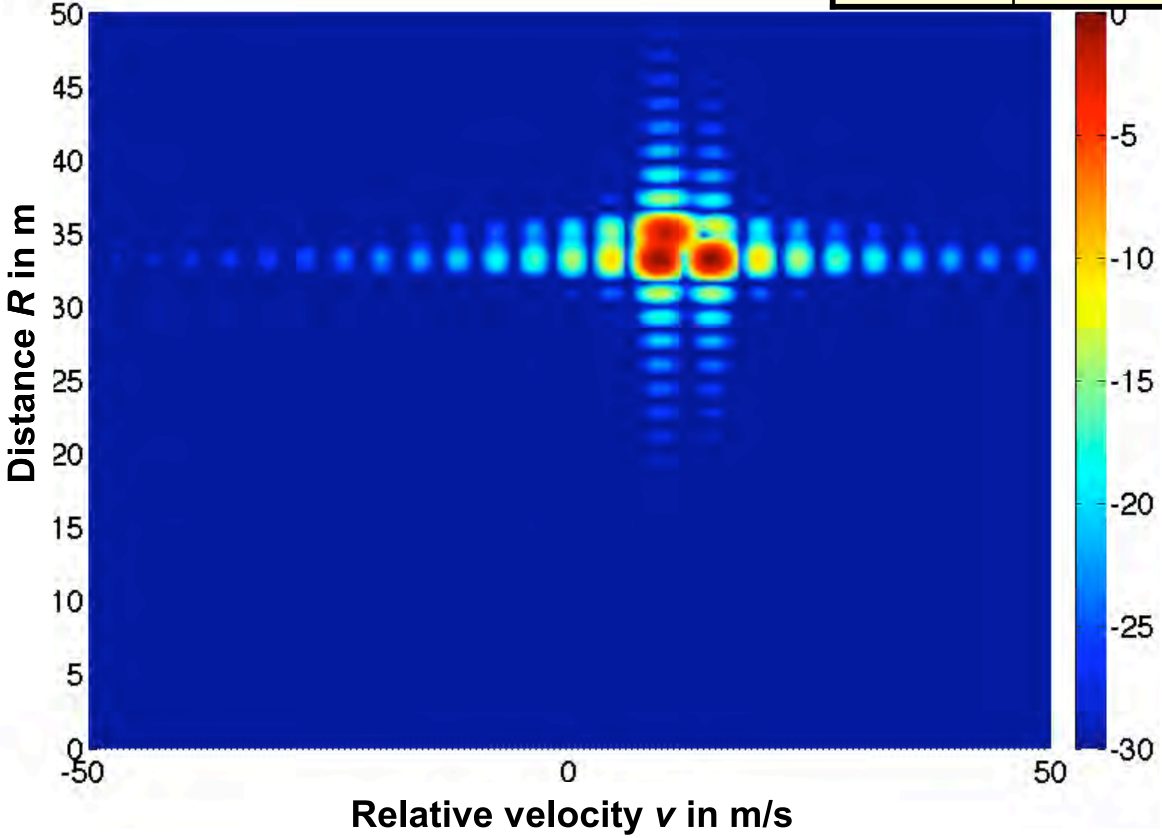


$$\Delta v = \frac{\lambda}{2T_{sym}N_{sym}} = 3.95m$$

Simulation result :
$\Delta v = 4m/s$

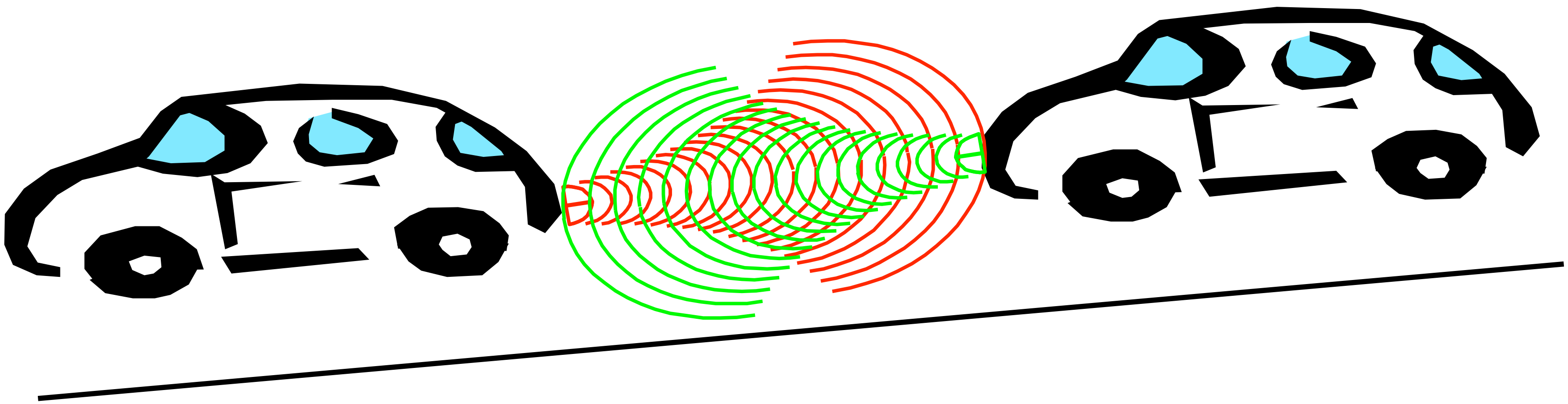
Range and Doppler Resolution for 3 Targets

Target	Range *R* in m	Speed *v* in m/s
z_1	33,2	10
z_2	33,2	14
z_3	35	10



Unambiguous and independent resolution for distance and Doppler for an arbitrary number of objects

Radar and Communication Ranges



Radar equation:

$$P_{RRadar} = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4}$$

Communication range:

$$P_{RCom} = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2 \cdot R^2}$$

$$P_{RCom} = P_{RRadar} \cdot \frac{4\pi \cdot R^2}{\sigma}$$

Range Comparison for Radar and Communications

Radar Range R_R:

$$R_{\max} = \sqrt[4]{\frac{P_{Tx} G_{Tx} G_{Rx} \sigma \cdot \lambda^2}{P_{Rx\ \min} \cdot (4\pi)^3}}$$

Free space propagation

$$P_{Rx\ \min} = -114\, dBm + 10 \log B / MHz + SNR / db + NF / dB$$

Required SNR depends on:
-Integration
-POD, FAR

Com. Range R_{com}:

$$R_{\max} = \sqrt[2]{\frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2}{P_{Rx\ \min} \cdot (4\pi)^2}}$$

Free space propagation

$$P_{Rx\ \min} = -114\, dBm + 10 \log B / MHz + SNR / db + NF / dB$$

Required SNR depends on:
-Coding
-BER, PER

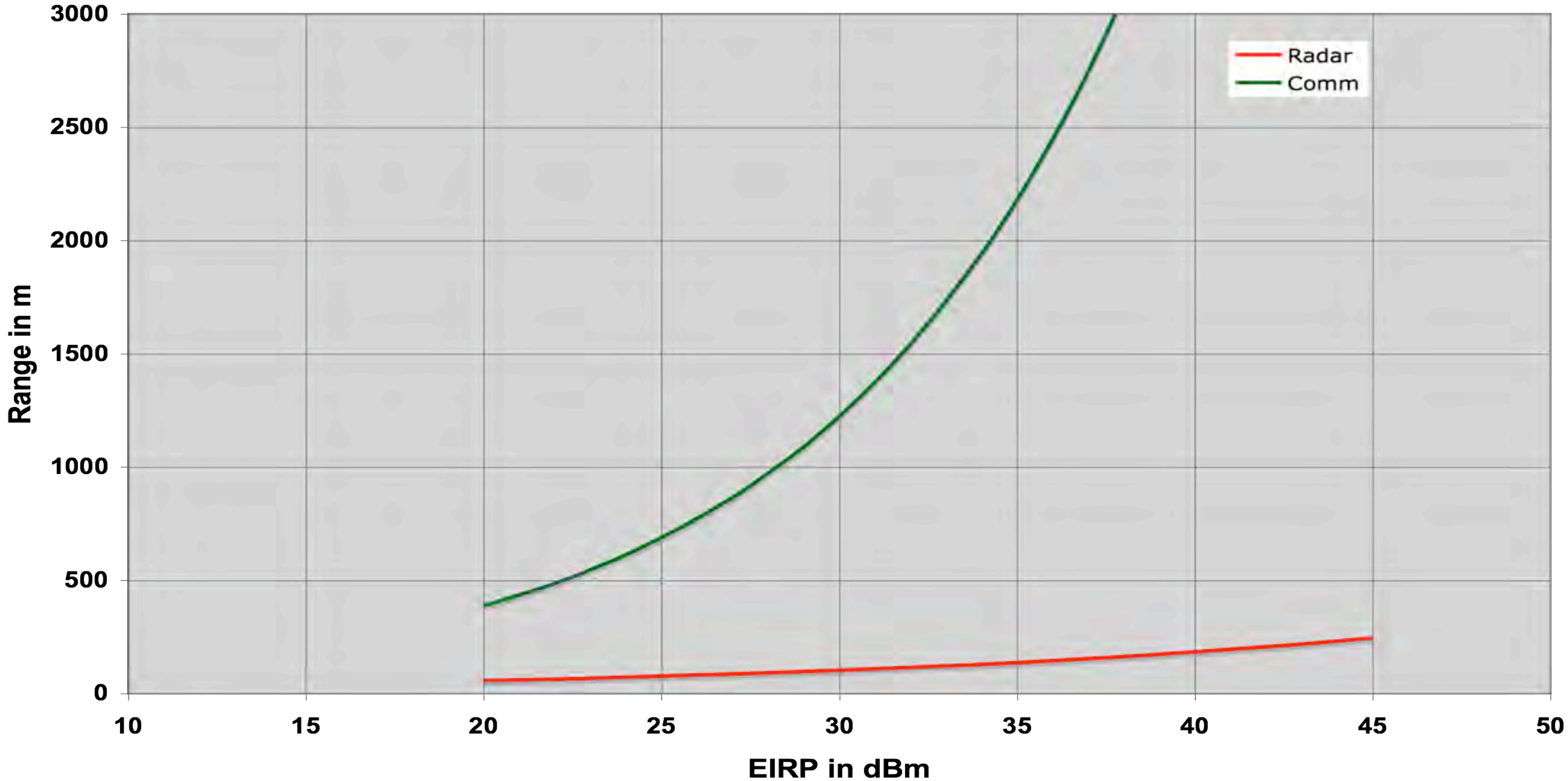
Range Comparison for Radar and Communications

System Data:

f_{Tx} = 24 GHz
B = 500 MHz

Radar:
σ_{min} = 0 dBm²
G_{Rx} = 35 dBi
$SNR \geq$ 14dB

Communication:
G_{Rx} = 6 dBi
$SNR \geq$ 14 dB



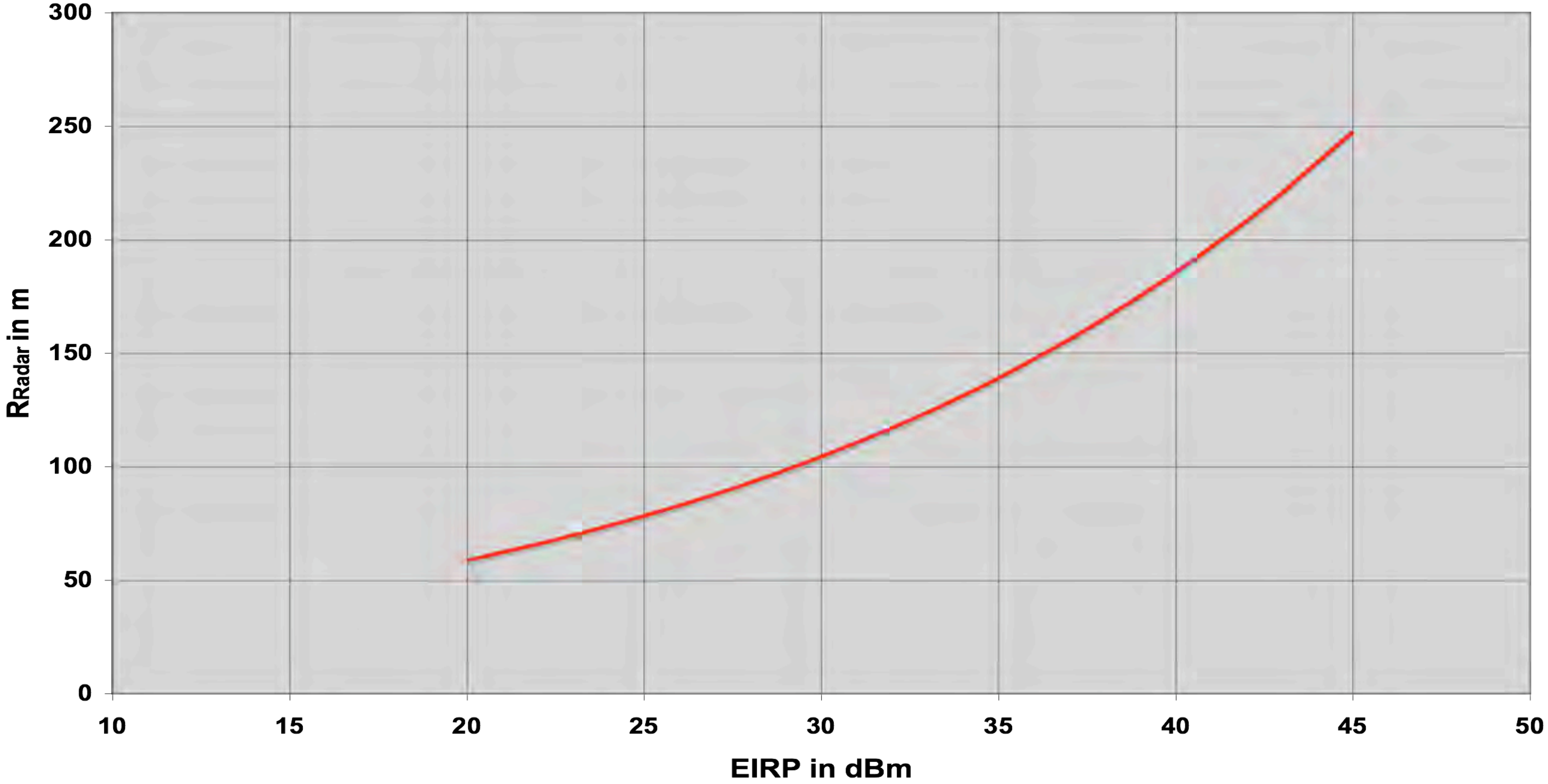
Range Comparison for Radar and Communications

System Data:

f_{Tx} = 24 GHz
B = 500 MHz

Radar:
σ_{min} = 0 dBm²
G_{Rx} = 35 dBi
SNR ≥ 14dB

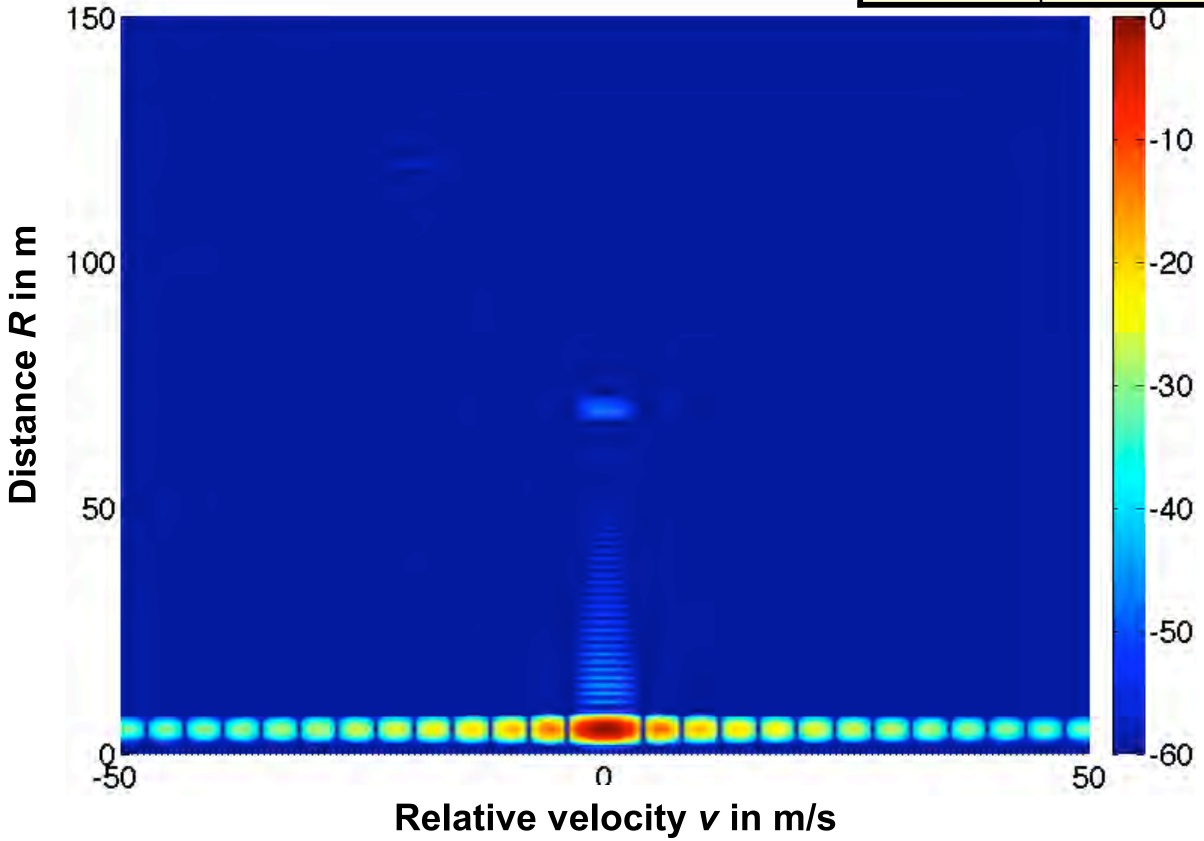
Communication:
G_{Rx} = 6 dBi
SNR ≥ 14 dB



Performance for Close Objects: Example for 3 Targets

identical RCS σ

Target	Range R in m	Rel. P_{Rx} in dB
z_1	5	0
z_2	70	-45,8
z_3	120	-55,2



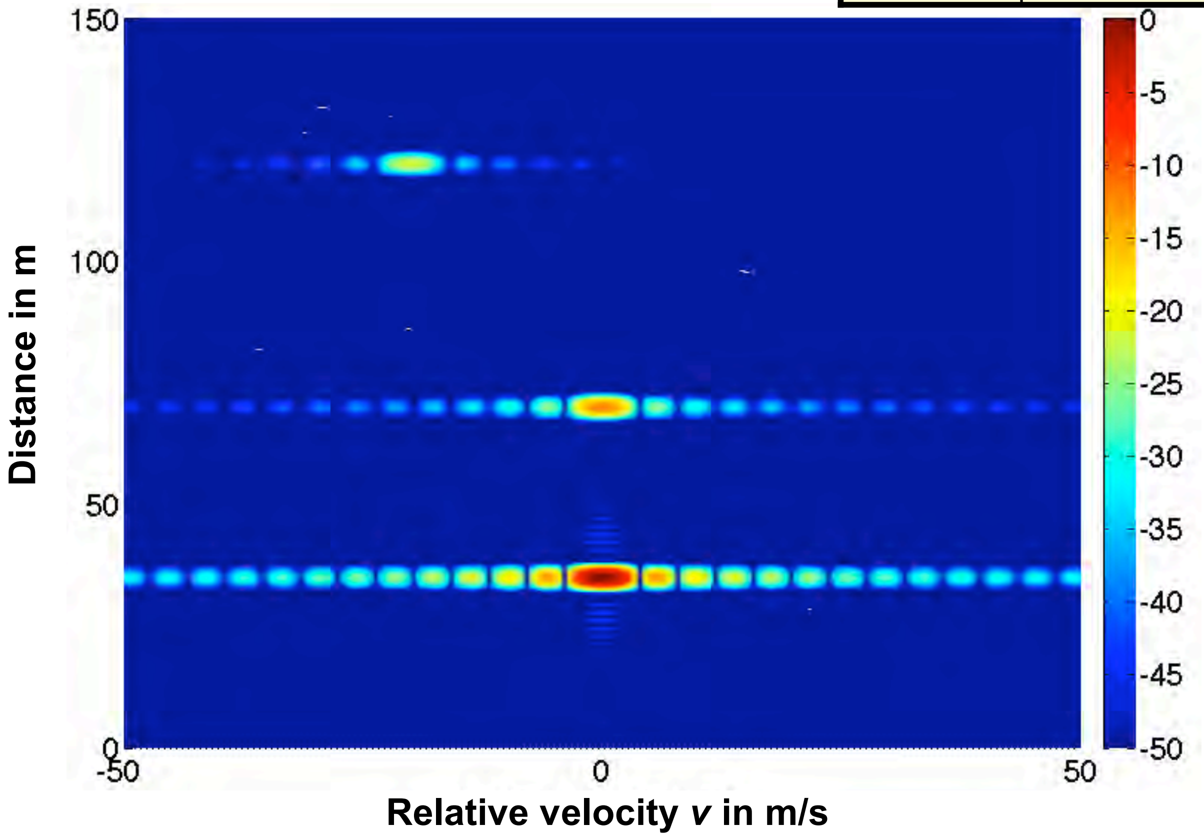
Close objects severly degrade range performance

Problem: Dynamic range

Distributed 3 Targets

identical RCS σ

Target	Range R in m	Rel. P_{Rx} in dB
z_1	35	0
z_2	70	--12
z_3	120	-21,4



Antenna Coupling Effect

Target	Range R in m	Speed v in m/s
z_1	40	-30
z_2	50	10

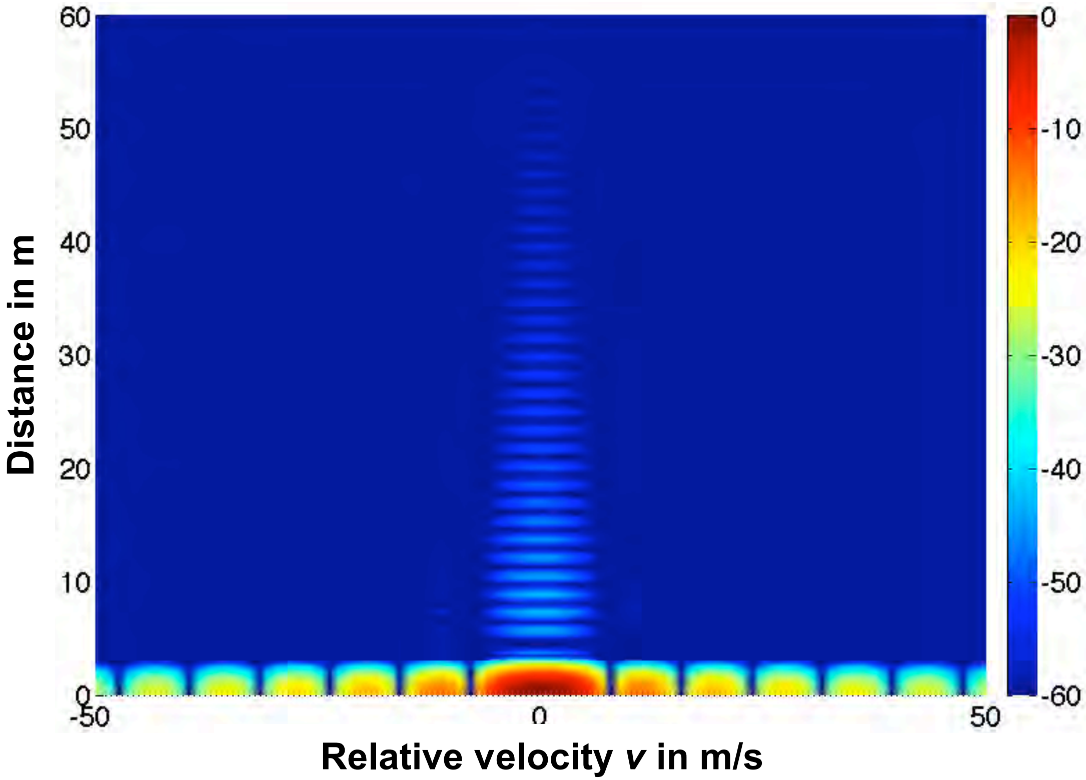
Identical RCS σ
Tx and Rx antenna coupling coefficient C

Example 1:
- C =-30dB
- two targets

$$\frac{P_{Rx-40m}}{P_{coupl}} = -95\ \text{dBm}$$

$$\frac{P_{Rx-50m}}{P_{coupl}} = -99\ \text{dBm}$$

→ **targets hidden by coupling**



Universität Karlsruhe (TH)
Research University • founded 1825

Institut für Höchstfrequenztechnik und Elektronik

Antenna Coupling Effect

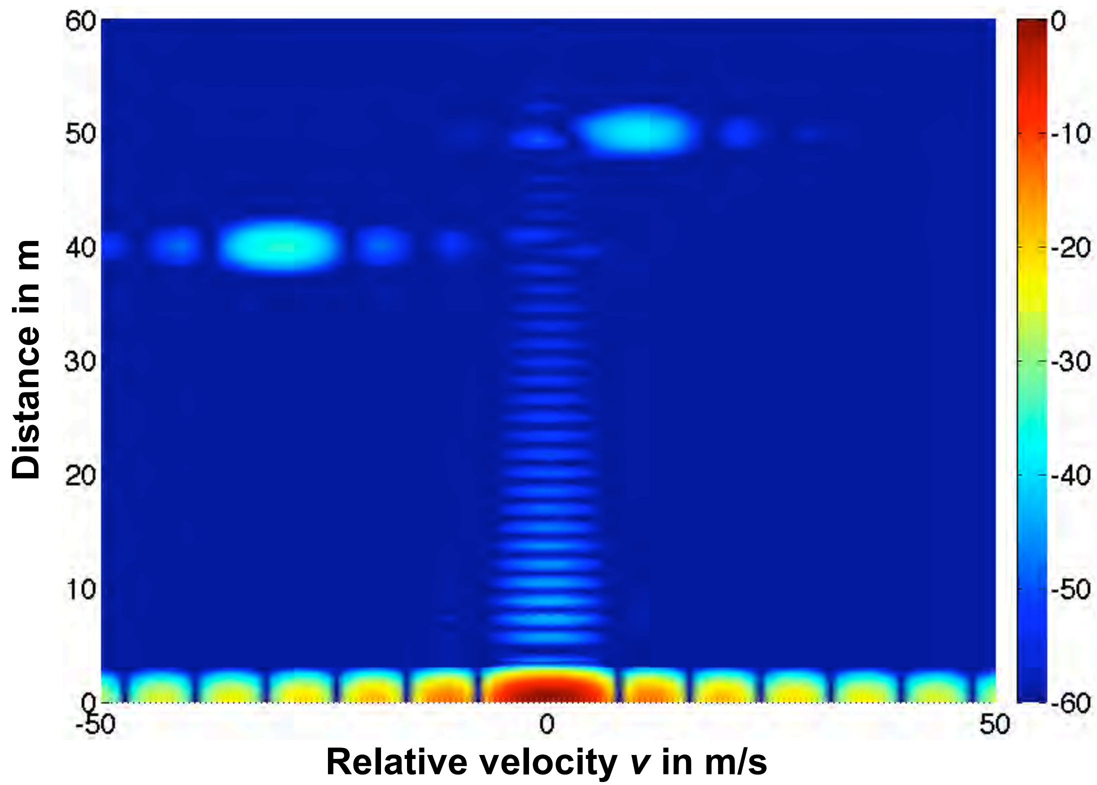
Identical RCS σ
Tx and Rx antenna coupling coefficient *C*

Target	Range *R* in m	Speed *v* in m/s
z_1	40	-30
z_2	50	10

Example 2:,
- ***C* =-45dB**
- **two targets**

$$\frac{P_{Rx-40m}}{P_{coupl}} = -80\ \text{dBm}$$

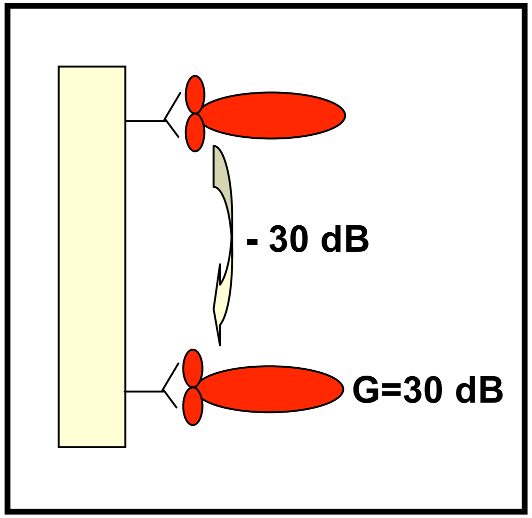
$$\frac{P_{Rx-50m}}{P_{coupl}} = -84\ \text{dBm}$$

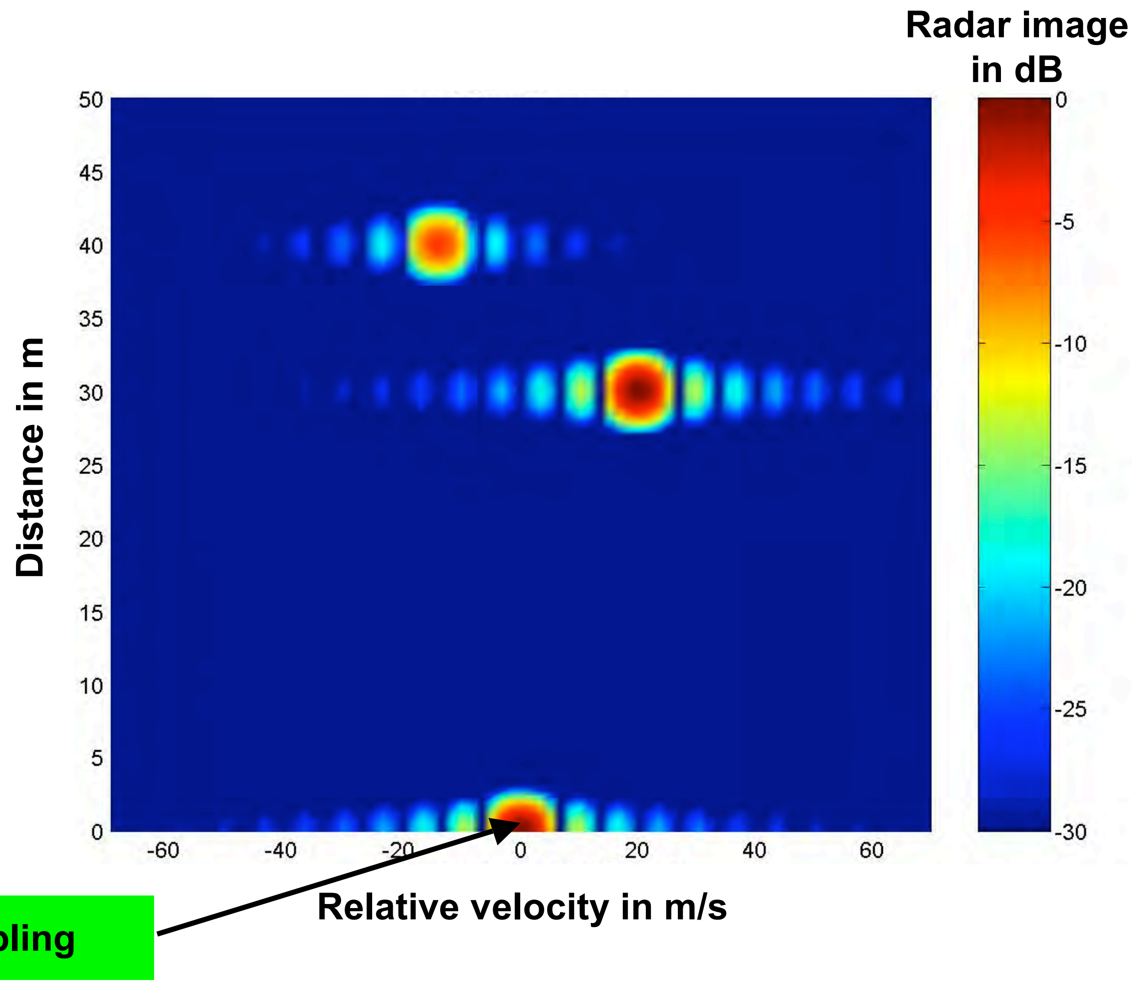


targets visible

Antenna Coupling

Total isolation
-60 dB





Coding of Radar Signals

Well known Radar coding for EW purposes:

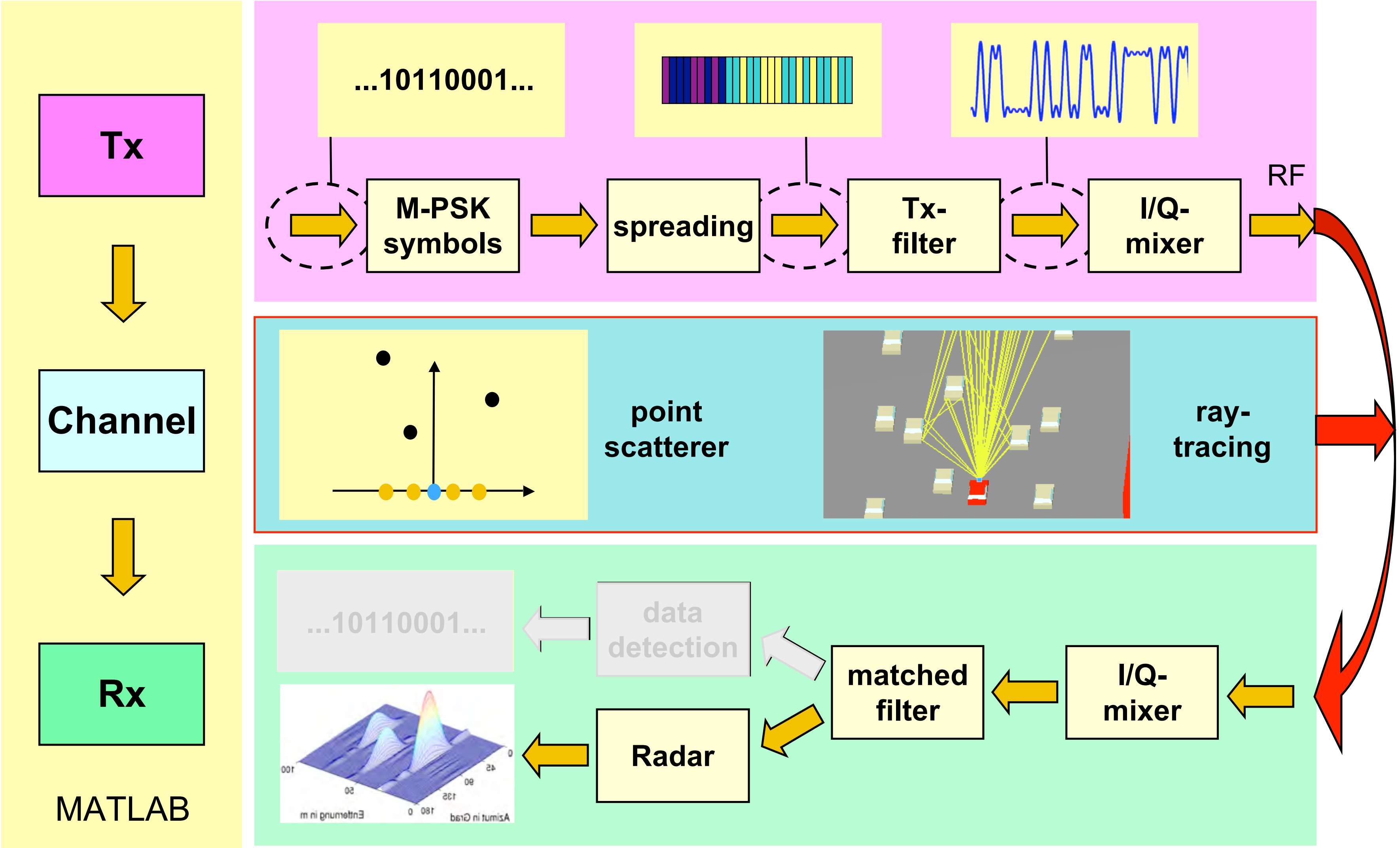
- Staggering
- Puls position modulation (PPM)
- Phase coding
- Frequency hopping
- ......

Coding in communications:

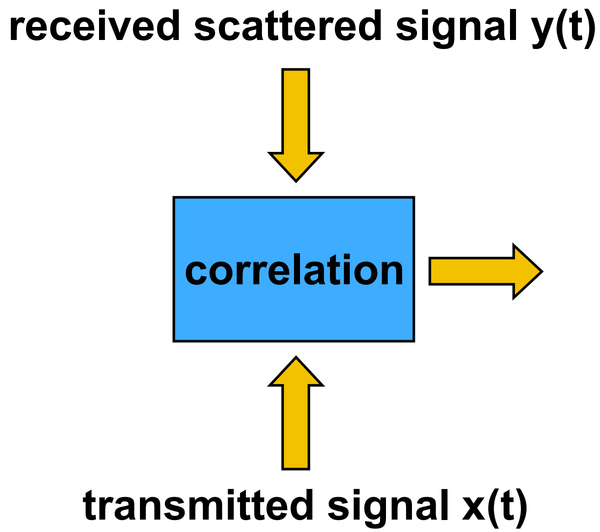
- BPSK, QPSK
- OFDM
- CDMA
- ......

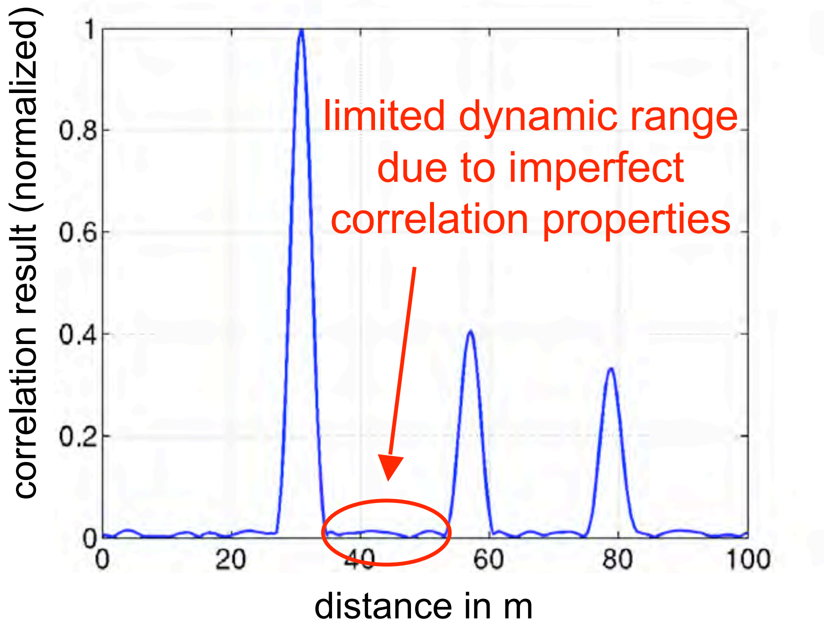
BPSK

Radar+Communication Simulation Tool



Range Processing





Correlation R: $$R_{XY}(t,\tau) = \int_0^{T_F} x(t)\ \ y(t+\tau)\ \ dt$$

Requirements

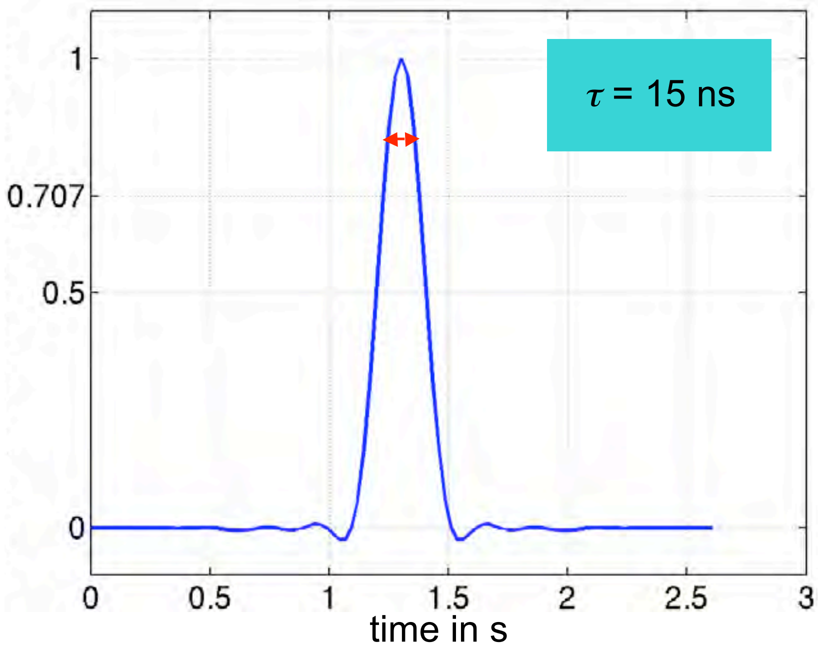
Optimal auto-correlation properties: $R_{XX}(t,\tau) = \delta(\tau)$

Signals from other users are uncorrelated: $R_{X1X2}(t,\tau) \equiv 0$

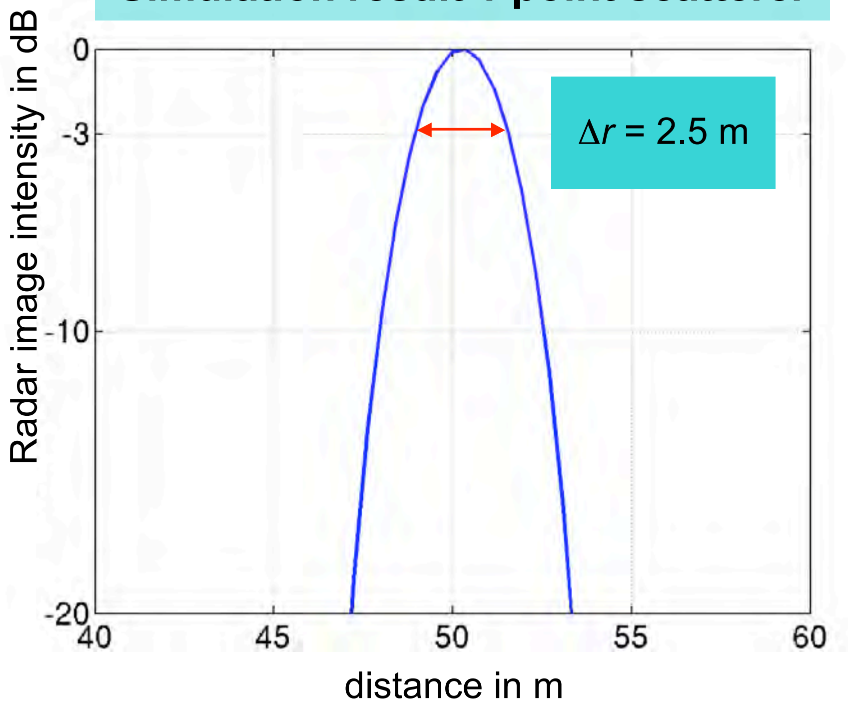
Proper spreading codes required!

Range Resolution

Matched filter response



Simulation result 1 point scatterer



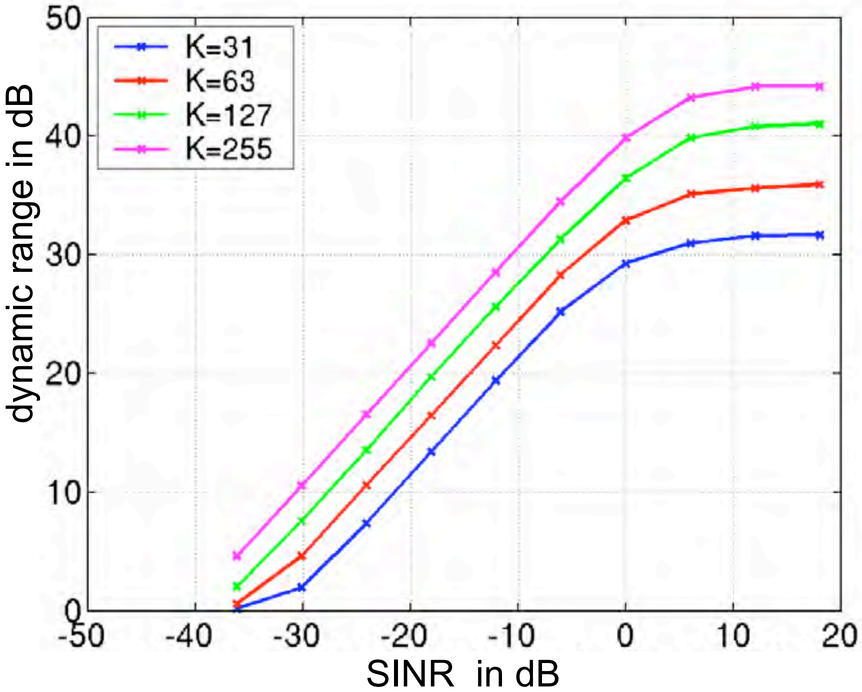
$$\Delta r = c_0\tau/2 = 2.25\text{ m}$$

Simulation Parameters:

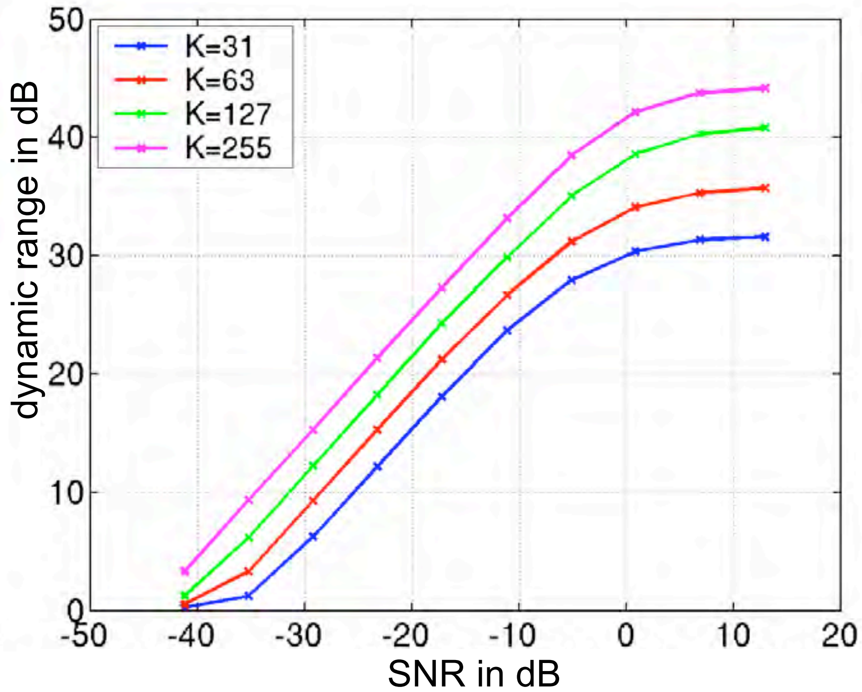
- **Root-raised cosine rolloff filters *r*=1**
- **Signal bandwidth 96 MHz**
- **48 MChips/s, *K*=127**

Performance Analysis for Interference and Noise

Interference from 2nd user



Gaussian Noise



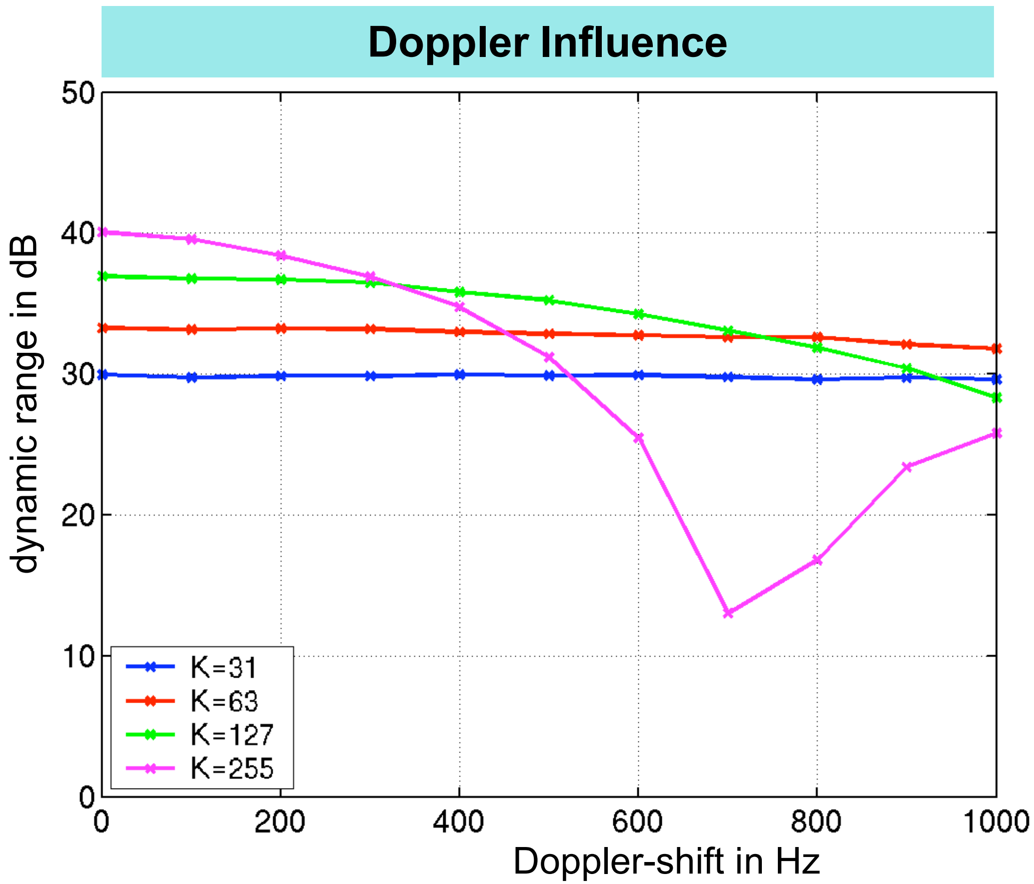
Spreading code:

- **M-Sequence *K* (length 2^{17}-1)**
- **Second user has different M-sequence**

Simulation Parameters:

- **2-PSK**
- **48 MChips/s**
- **Frame-length 256 data symbols**

Performance Analysis of the Doppler Influence



Simulation Parameters:

- **2-PSK**
- **48 MChips/s**
- **Two users, SINR 0 dB**
- **Frame-length 256 data symbols**
- **Transmission frequency 2 GHz**

1000 Hz ≈ 270 km/h

Spreading factor K > 127
Significant degradation of dynamic range at high velocities

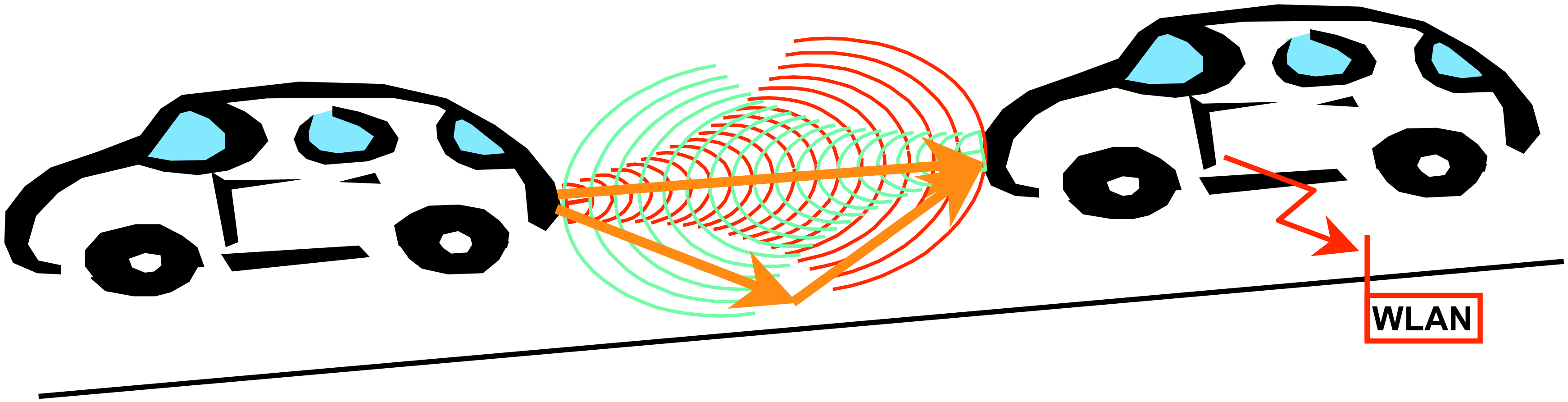
Digital Beam-forming and Super-Resolution Demonstrated for BPSK

by Christian Sturm and Werner Wiesbeck

Universität Karlsruhe (TH)
Research University • founded 1825

Institut für Höchstfrequenztechnik und Elektronik
IHE

Multiple Antenna Systems⇒High Resolution Algorithms



Multiple Antenna Systems:

- **Beam-Forming,**
- **Diversity**
- **MIMO**
- **Interference suppression**

Adaption trafic:

- **urban**
- **free way....**

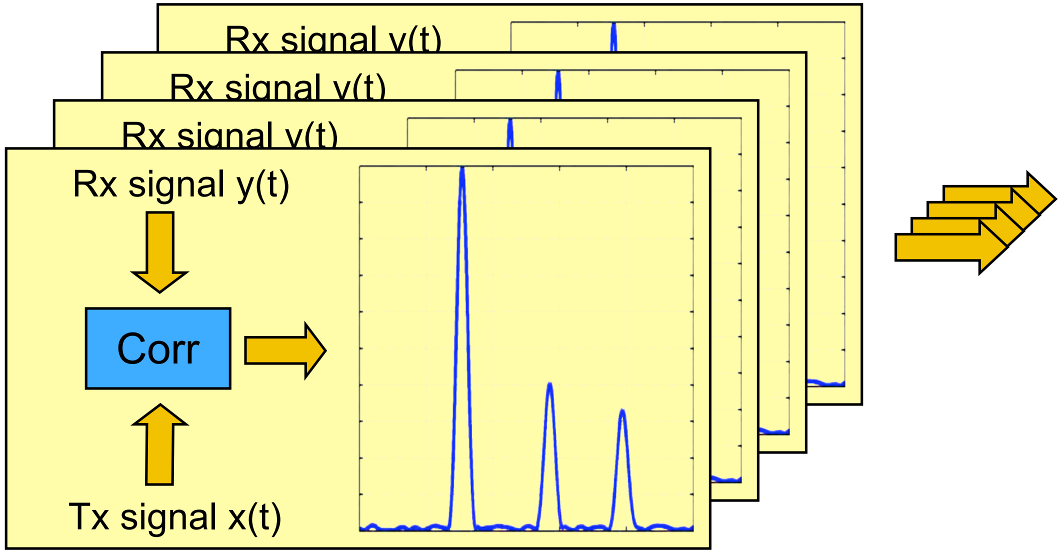
Radar und Communication with Digital Beam-forming

Combined SRR und ACC by digital Beam-forming

- **Direction by Super-Resolution (or classial beam-forming)**
- **Range by coding (PN-Codes, PPM, OFDM, MPSK.**

Communication V2V by Codes

Azimuth Processing: Smart Antenna Techniques



$$\begin{pmatrix} R_{XY_0}(\tau) \\ R_{XY_1}(\tau) \\ R_{XY_2}(\tau) \\ R_{XY_3}(\tau) \end{pmatrix} = \vec{R}_{XY}(\tau)$$

array signal vector

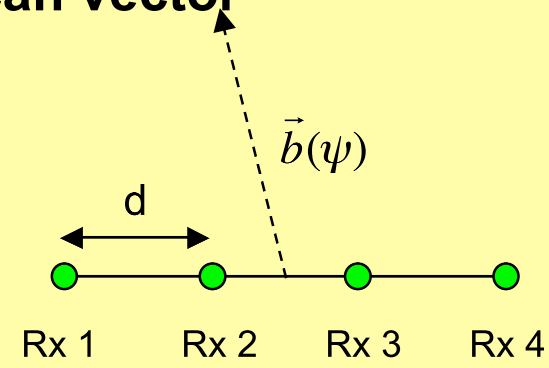
smart antenna algorithms

4 independent receivers
(reasonable hardware effort)

Receiver spacing λ/2
(to avoid ambiguities)

Algorithm 1: Fourier Transform Approach

Scan vector



$$\vec{b}(\psi) = \begin{pmatrix} 1 \\ e^{j\sin(\psi)2\pi d/\lambda} \\ e^{j\sin(\psi)2\pi\, 2d/\lambda} \\ e^{j\sin(\psi)2\pi\, 3d/\lambda} \end{pmatrix}$$

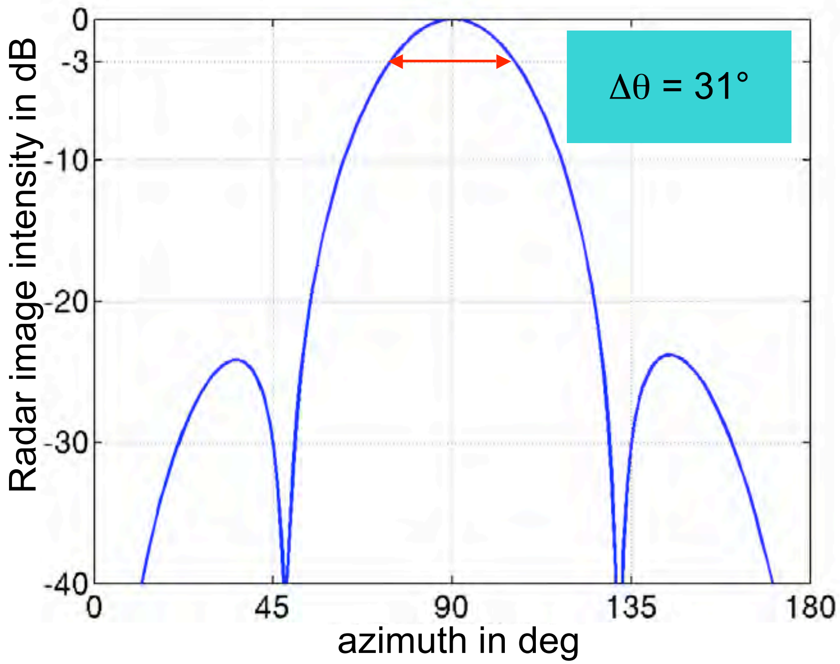
Radar image intensity:

$$I(\psi,\tau) = \left|\vec{R}_{XY}^{T}(\tau)\cdot\vec{b}(\psi)\right|^2 = \left|\sum_{n=0}^{3} R_{XY_n}(\tau)\cdot e^{jnu}\right|^2, \quad u = 2\pi\cdot\frac{d}{\lambda}\cdot\sin(\psi)$$

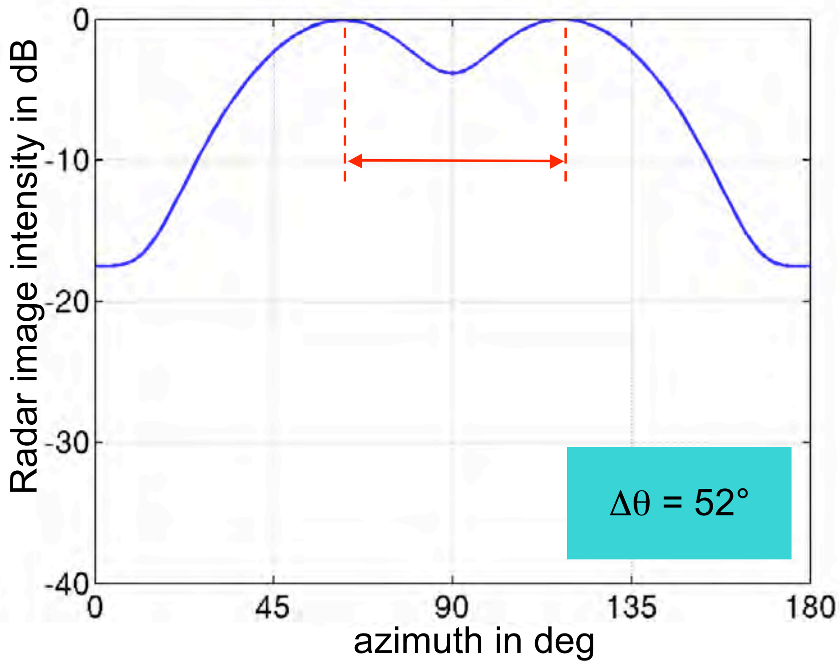
Discrete Fourier transform with angular distortion

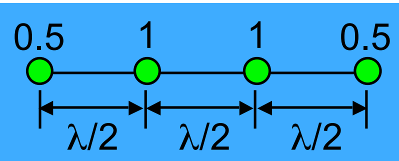
Azimuth Resolution

1 point scatterer



2 point scatterers

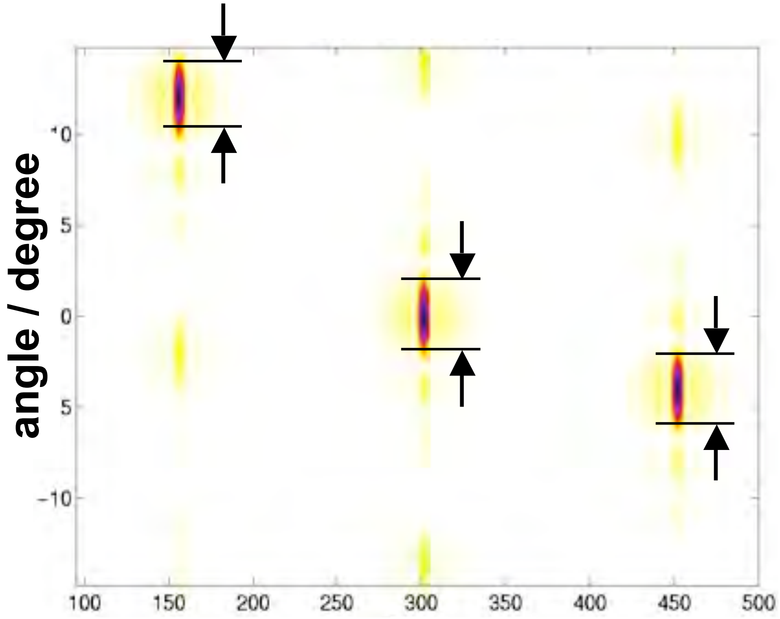




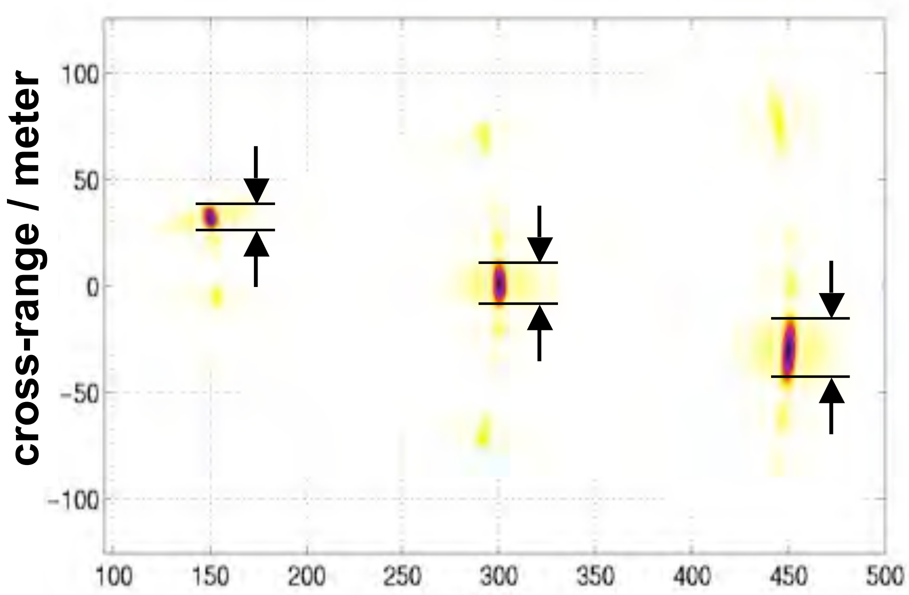
Not suitable for practical applications

Range Dependent Cross-Range Resolution

A constant angular resolution, e.g. antenna beam-width, translates into a range dependent spatial resolution. Thus the spatial resolution gets worse for increased distance to the radar.



range / meter



range / meter

Super-Resolution Algorithm: MUSIC

correlation matrix of received signals $\underline{R}_{\underline{uu}}$

basic idea of R-MUSIC
- statistical data
- a priori system knowledge
- point scatterer

signal $\underline{v}_1, \cdots, \underline{v}_p$ $\perp$ noise $\underline{v}_{p+1}, \cdots, \underline{v}_R$

system model $\underline{S} = \underline{H} \cdot \underline{o}$ → $\underline{h}_1, \cdots, \underline{h}_N$; $\alpha_1, \cdots, \alpha_N$

for an object at $\alpha_i \Leftrightarrow \underline{\mathbf{h}}_i \perp \underline{\mathbf{v}}_{noise}$ →

$$S_{R-MUSIC}(\alpha_i) = \frac{1}{\sum_{k=p+1}^{R} \left| \underline{h}_i^H \underline{v}_k \right|^2}$$

R-MUSIC: adapted to Radar applications

Algorithm 2: Subspace Approach (MUSIC)

Linear model for array signal vector

$$\vec{R}_{XY}(\tau_0) = \underbrace{\left[\vec{b}(\psi_1) \quad \cdots \quad \vec{b}(\psi_M)\right]}_{\mathbf{B}} \cdot \underbrace{\begin{pmatrix} a_1 \\ \vdots \\ a_M \end{pmatrix}}_{\vec{a}} + \vec{N}$$

Regarding one specific resolution cell τ_0

M incident signals (M<4)
a_i: complex weights
N: additive Noise (mean zero)

Correlation matrix

$$\mathbf{R}_{\varphi\varphi} = E\left\{\vec{\varphi}_{XY}(\tau_0)\vec{\varphi}_{XY}^{*T}(\tau_0)\right\} = \mathbf{B}\mathbf{R}_{aa}\mathbf{B}^{*T} + \sigma^2\mathbf{I}$$

Rank M → 4-M eigenvalues equal to zero

4-M eigenvalues equal to σ^2
→ number of incident signals

Recovery of signal directions:

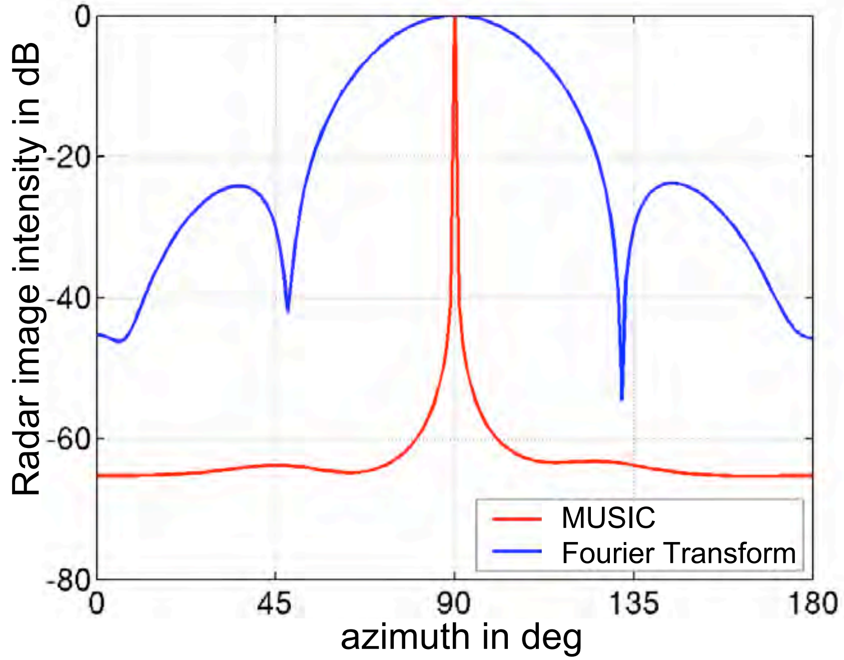
The 4-M eigenvectors $\vec{\xi}_i$ that are associated with eigenvalues $\lambda_i = \sigma^2$ are orthogonal to the subspace spanned by the columns of B → exhaustive search

Radar image intensity:

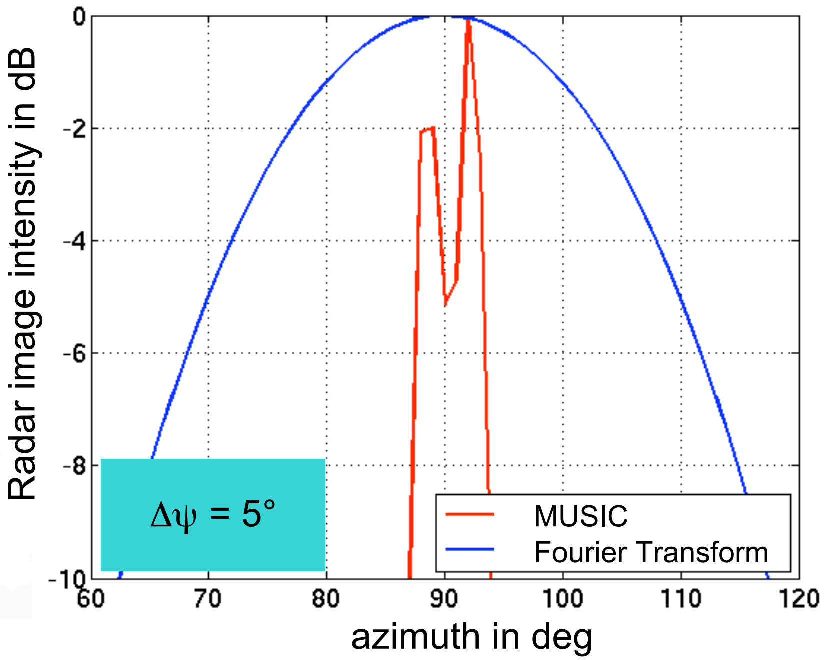
$$I(\psi) = \frac{1}{\sum_{i=1}^{4-M} \left|\vec{b}(\psi)\vec{\xi}_i\right|^2}$$

Azimuth Resolution Comparison: MUSIC-FFT

1 point scatterer

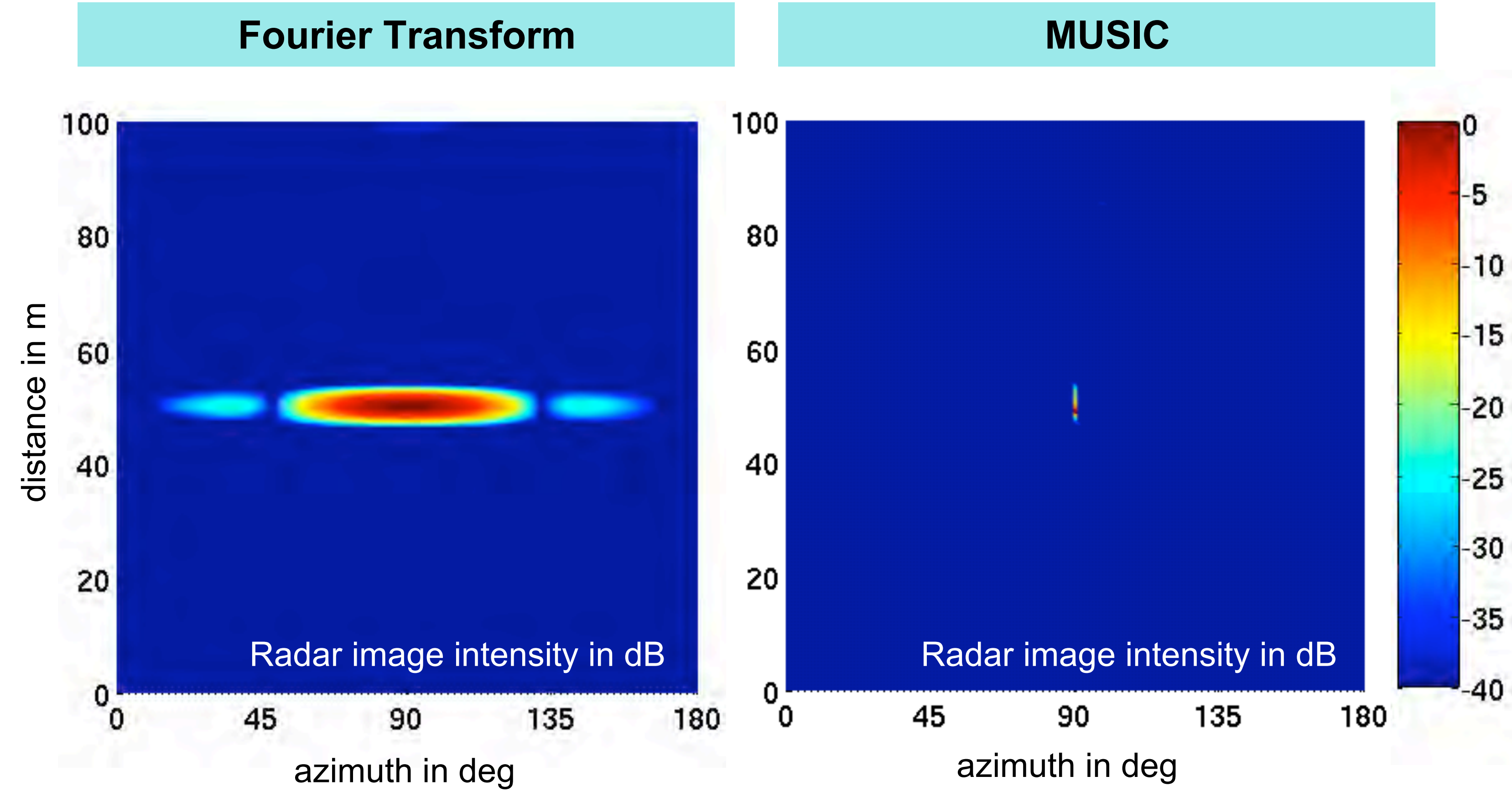


2 point scatterers in 5° distance



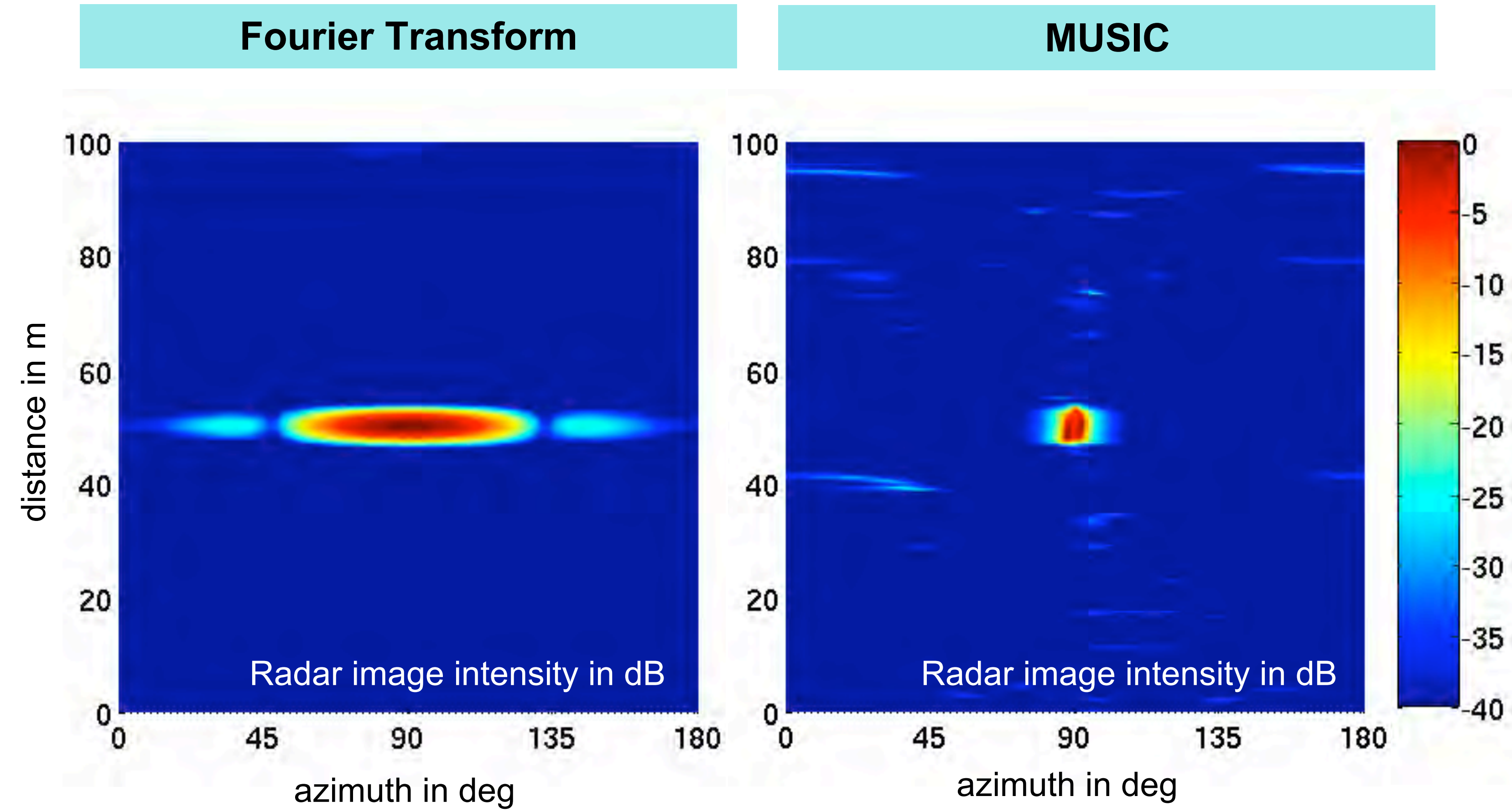
Correlation matrix estimation based on 8 uncorrelated snapshots
Fourier Transform with windowing (0.5,1,1,0.5) to reduce sidelobe level

2D Radar Images (1 Point Scatterer)



1 point scatterer, distance 50 m, azimuth 90°

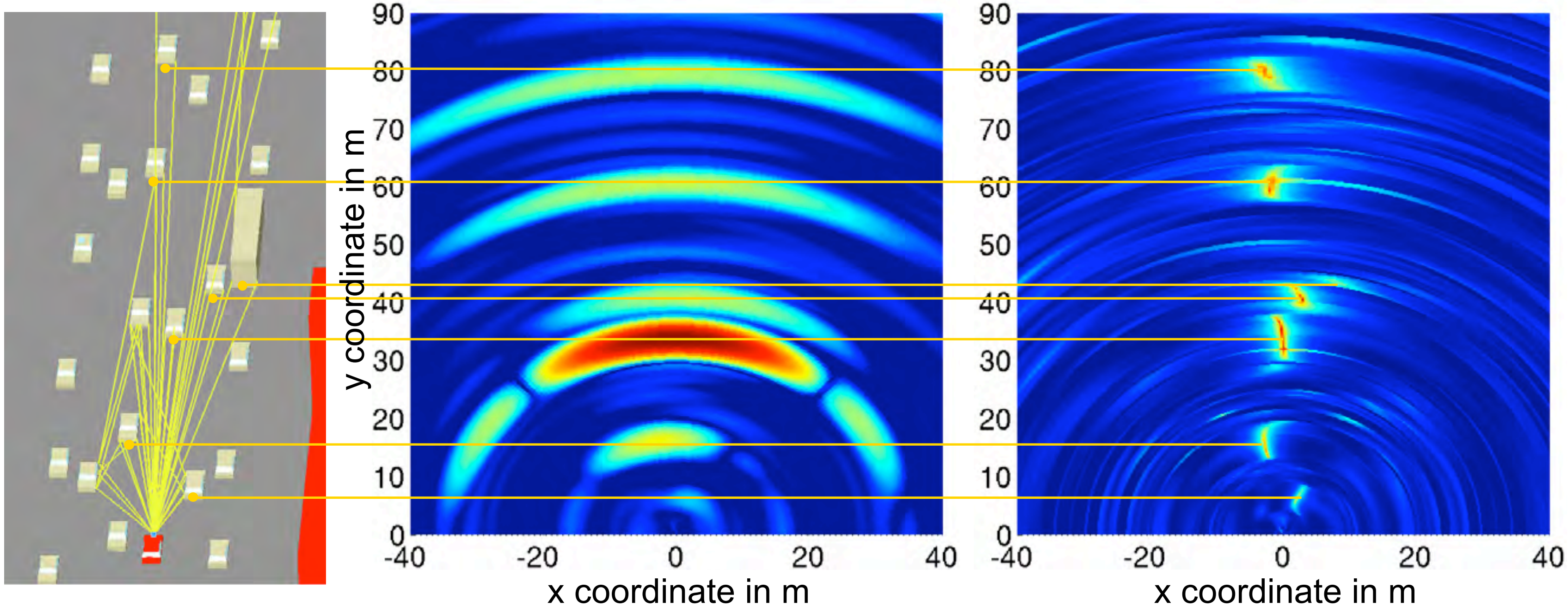
2D Radar Images (2 Point Scatterers)



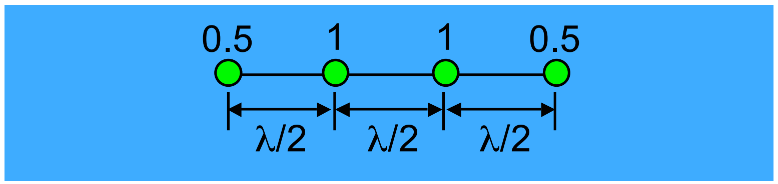
2 point scatterers, distance 50 m, azimuth 87.5° & 92.5°

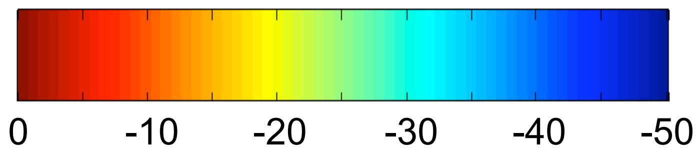
Propagation Modeling with Ray Tracer

Normalized Radar images in dB



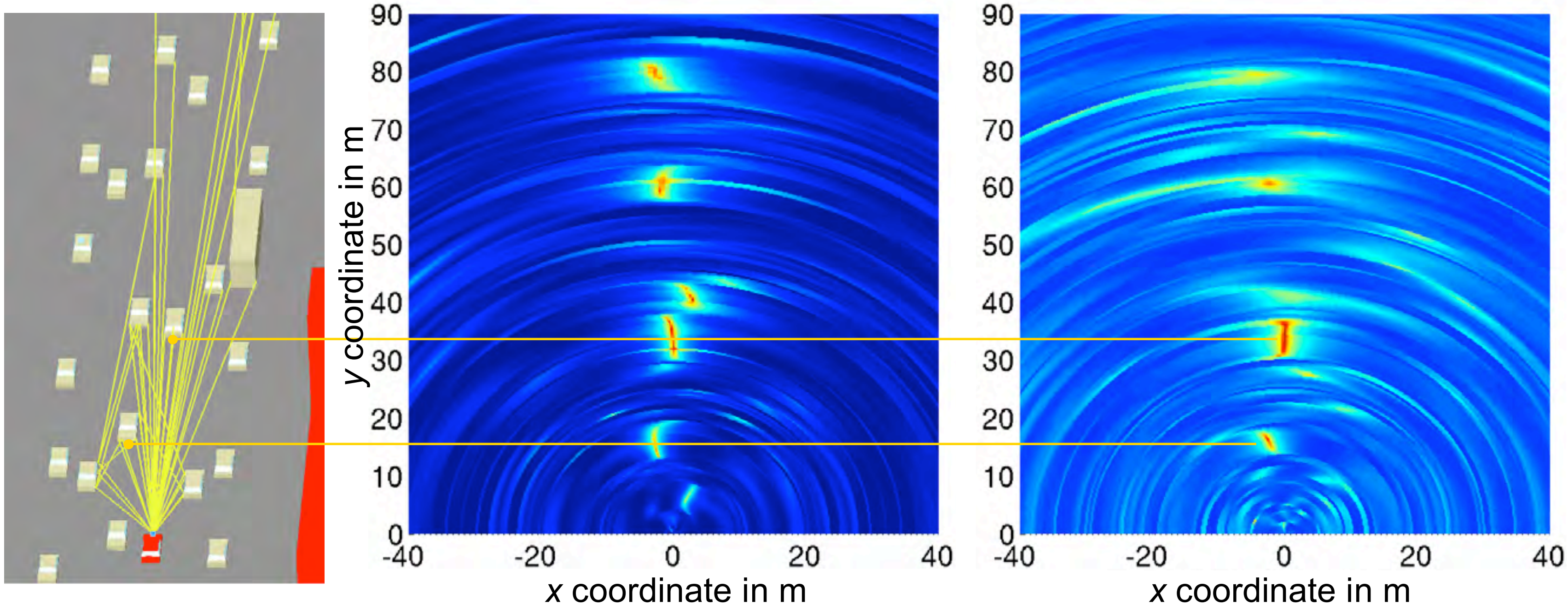
Fourier Transform **MUSIC**





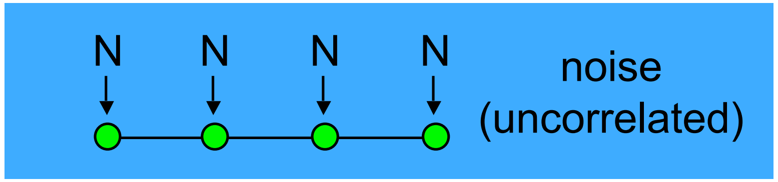
Performance of MUSIC in Noisy Environments

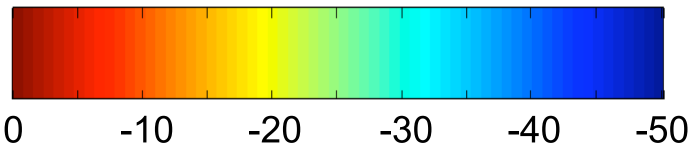
Normalized Radar images in dB



***SNR*: - 4.5 dB**

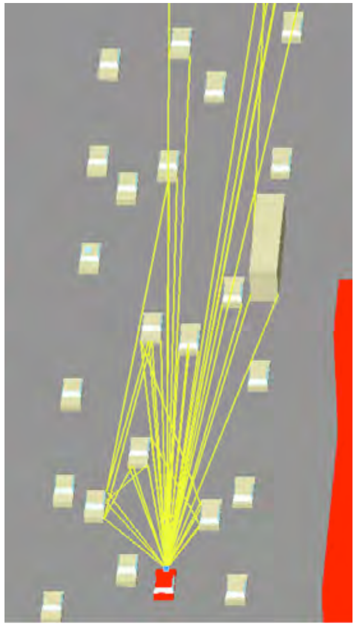
***SNR*: - 20 dB**

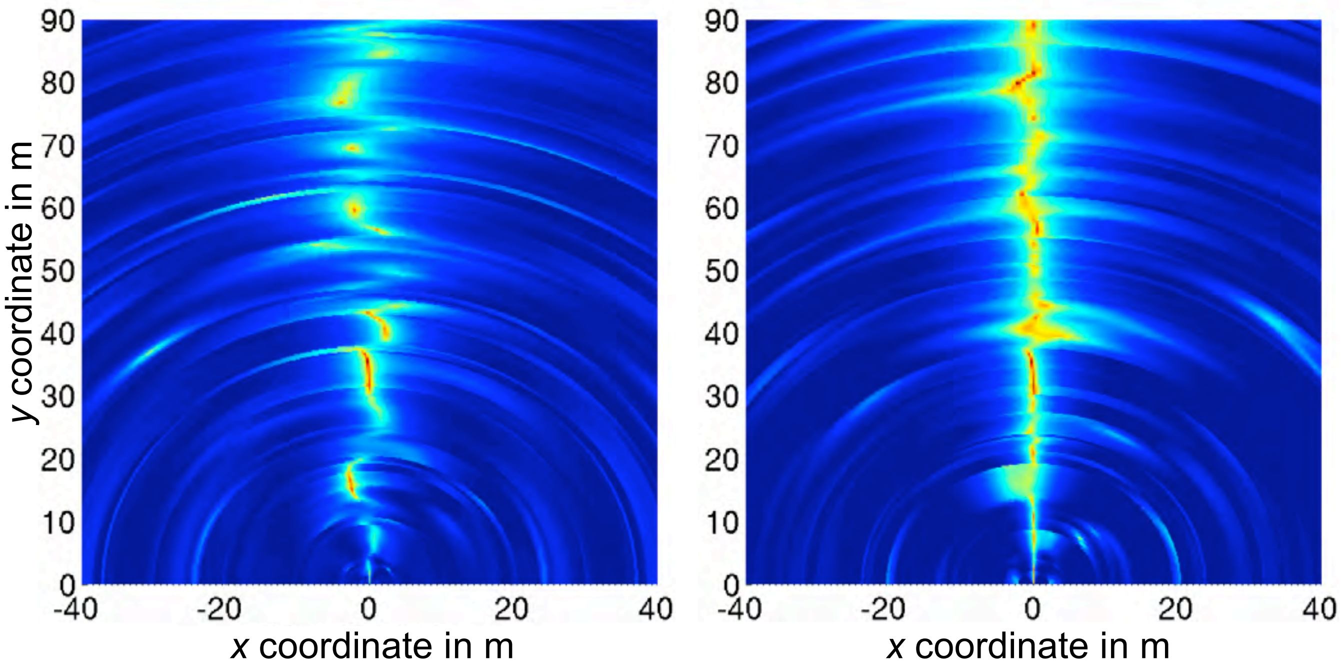




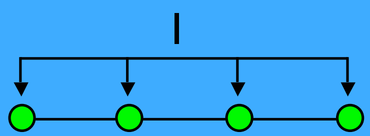
Perfomance of MUSIC with Interference

Normalized Radar images in dB

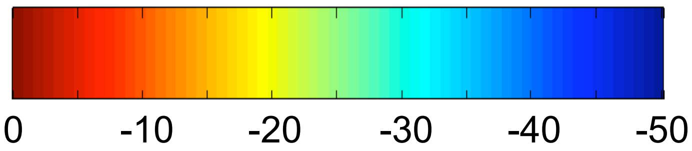




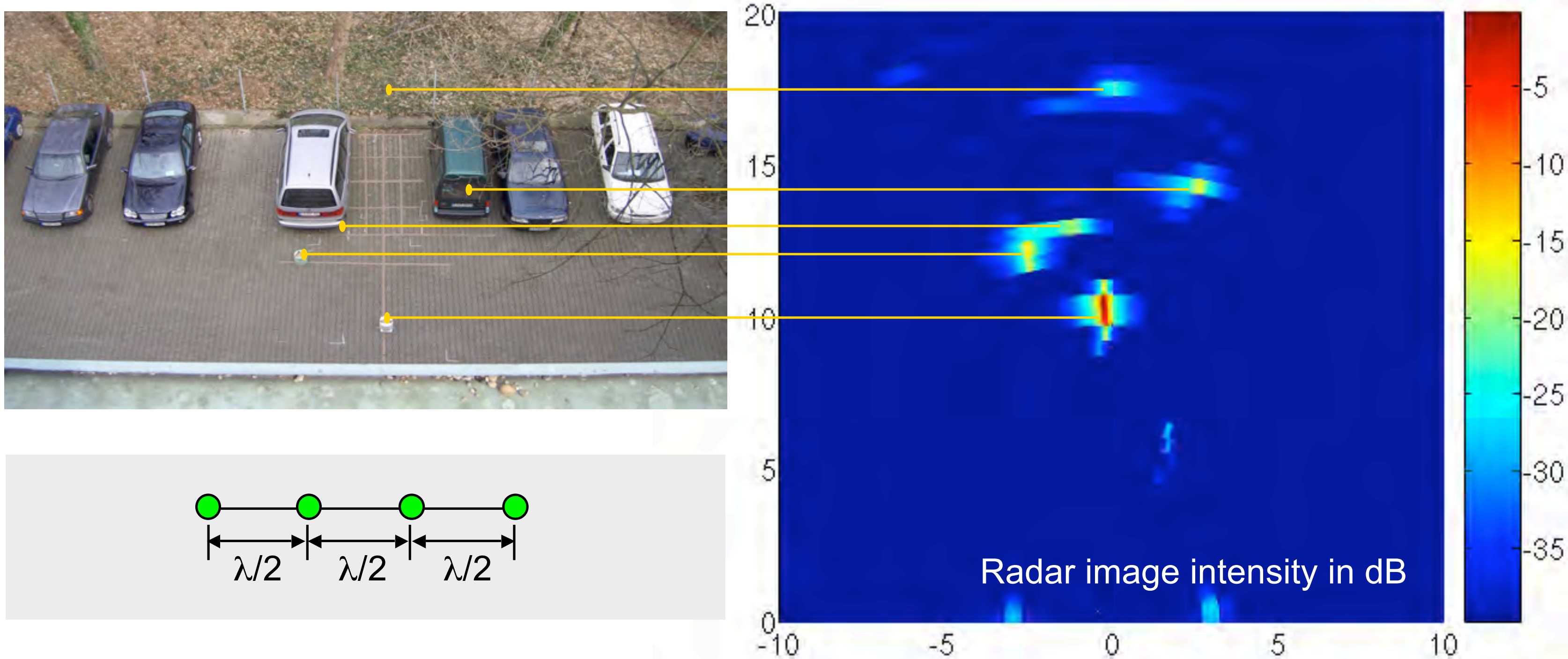
***SNIR*: - 4.5 dB** | ***SNIR*: - 20 dB**



interference (correlated)



Measurement Result MUSIC (Low Bandwidth)



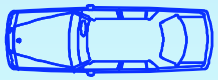
- **bandwidth *B* = 300 MHz**
- **frequeny range: 22.85 - 23.15 GHz**
- **8 snapshots**
- **241 steps FSCW**

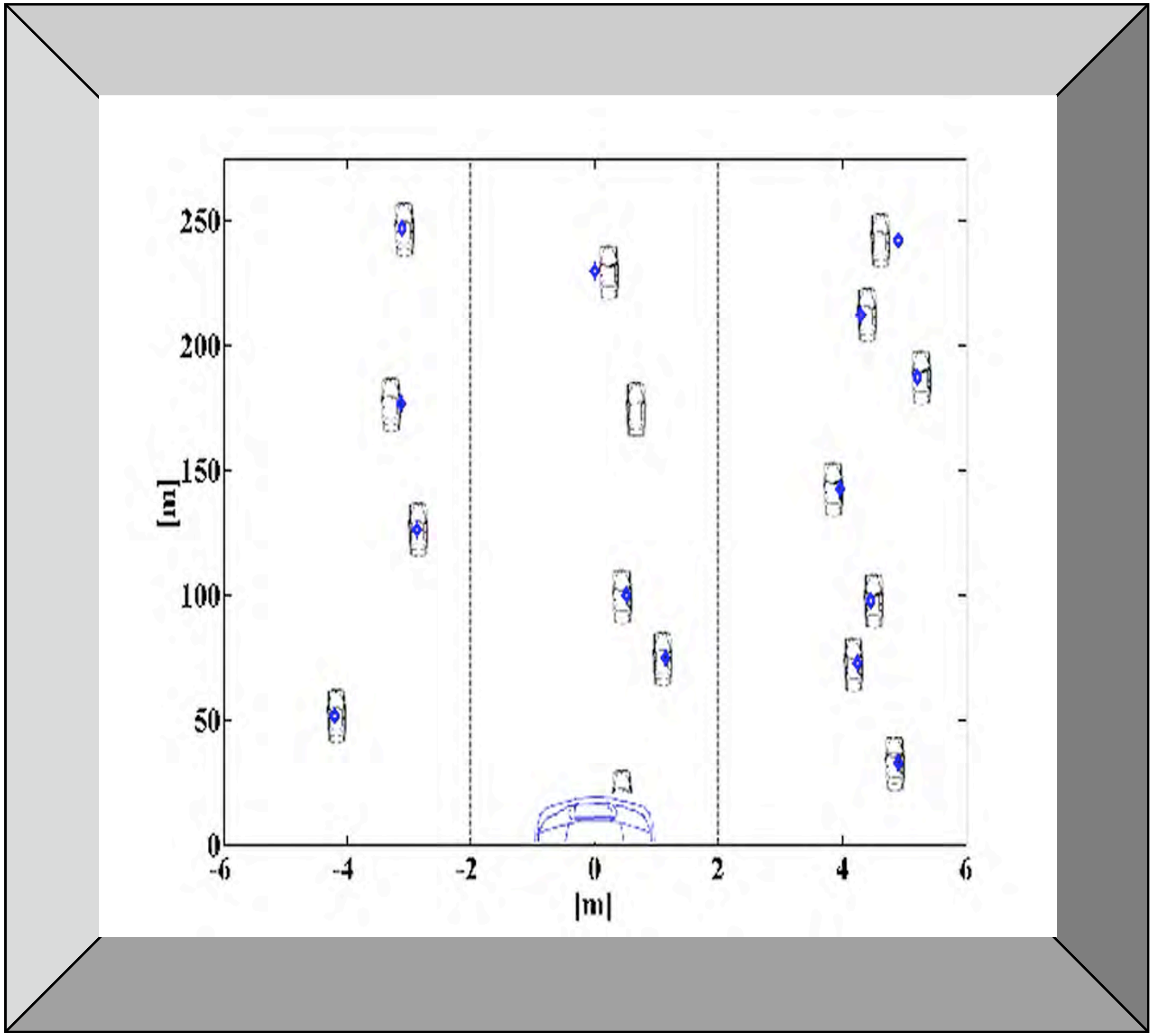
Simulation of Super-Resolution

3 lanes

cell size:
- **0,5m range**
- **0,15° azimuth**

system:
- **2 transmitters**
- **3 receivers**

objects:
- **real** 
- **detected** ◇



Summary

It has been shown that it is possible to use the spectrum simultaneously for Radar and Communication.

The insertion of BPSK or OFDM coded information is suitable for high resolution Radar application with *Digital Beam-forming* and Super-Resolution *Radar-MUSIK* Algorithm.

The presented idea could save wide frequency spectra in terrestrial and space-borne Radar and data transfer applications.