The Wireless MIMO Channel:

Measurements, Double-Directional Parameters, and Capacity

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Kplus
Kompetenzzentren-Programm

What is MIMO ?

- Multiple-Input, Multiple-Output
- Antenna arrays at both sides of the radio link
- aka „Dual Antenna Array“ technology
- So what is the hype about?

Wireless MIMO Channels:

Don‘t model them ...

... before you have measured them!

Outline

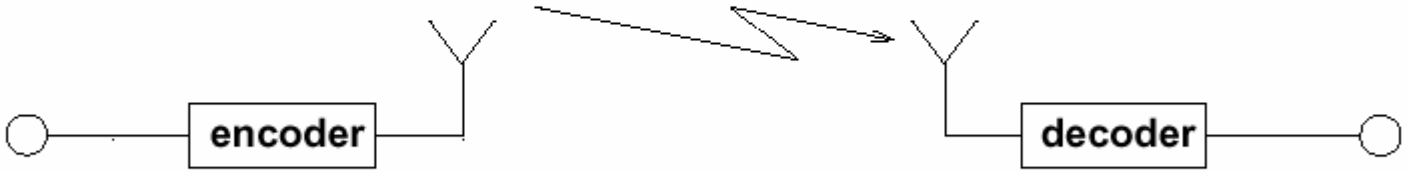
- Part I: Why bother?
- Part II: Analysis of Channel Measurements
- Part III: Alamouti's Space-Time Diversity Code

Part I

Motivation

Single-Input, Single-Output ...

Channel Capacity



Electro–magnetic waves via empty space:

$$R < B \cdot \log_2\left(1 + \frac{E_b}{N_0} \cdot \frac{R}{B}\right)$$

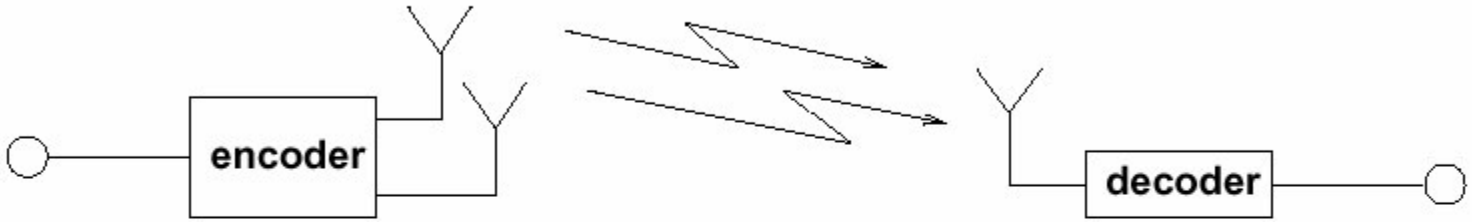
bit rate $\approx$ bandwidth · logarithm of energy

bit/s Hz bit

Bit rate is linear in bandwidth, but logarithmic in energy.

Multiple-Input, Single-Output ...

Single Antenna Array



Electro–magnetic waves via empty space:

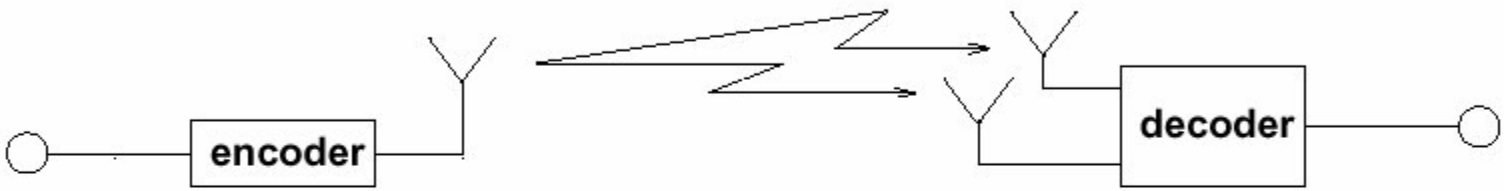
$$R < B \cdot \log_2\left(1 + \frac{2E_b}{N_0} \cdot \frac{R}{B}\right)$$

bit rate $\approx$ bandwidth $\cdot$ logarithm of energy

bit/s Hz bit

Single-Input, Multiple-Output ...

Single Antenna Array



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$$R < B \cdot \log_2\left(1 + \frac{2E_b}{N_0} \cdot \frac{R}{B}\right)$$

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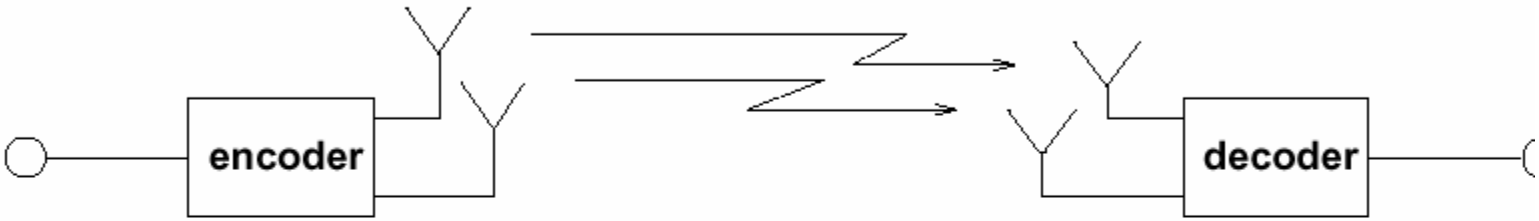
The MIMO promise ...

Dual Antenna Arrays



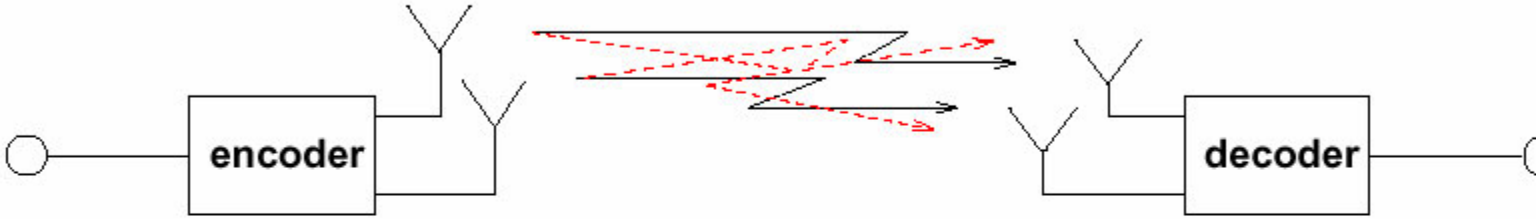
Electro–magnetic waves via empty space:

$$R < B \cdot \log_2 \det\left(\mathbf{I} + \mathbf{H}^{\dagger}\mathbf{H}\frac{E_b}{N_0}\cdot\frac{R}{B}\right)$$

$$= 2B \cdot \log_2\left(1 + \frac{E_b}{N_0}\cdot\frac{R}{B}\right) \quad \text{for} \quad \mathbf{H}=\mathbf{I}$$

However, in reality ...

Dual Antenna Arrays



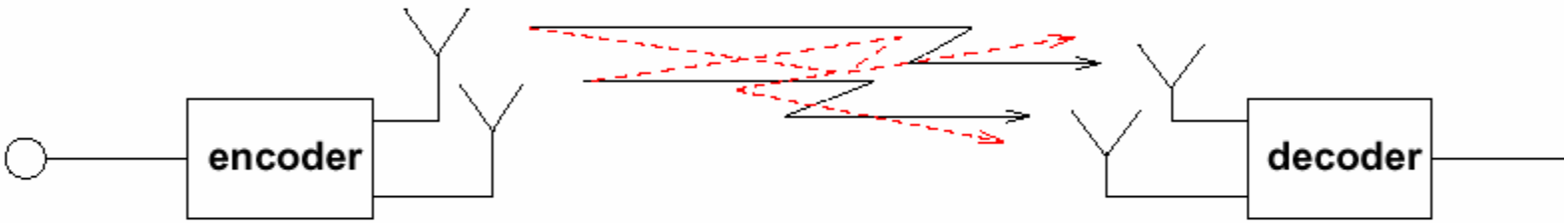
Electro–magnetic waves via empty space:

$$R < B \cdot \log_2 \det\left(\mathbf{I} + \mathbf{H}^{\dagger}\mathbf{H}\frac{E_b}{N_0}\cdot\frac{R}{B}\right)$$

$$\overset{?}{\approx} 2B \cdot \log_2\left(1 + \frac{E_b}{N_0}\cdot\frac{R}{B}\right) \quad \text{for} \quad \mathbf{H} \neq \mathbf{I}$$

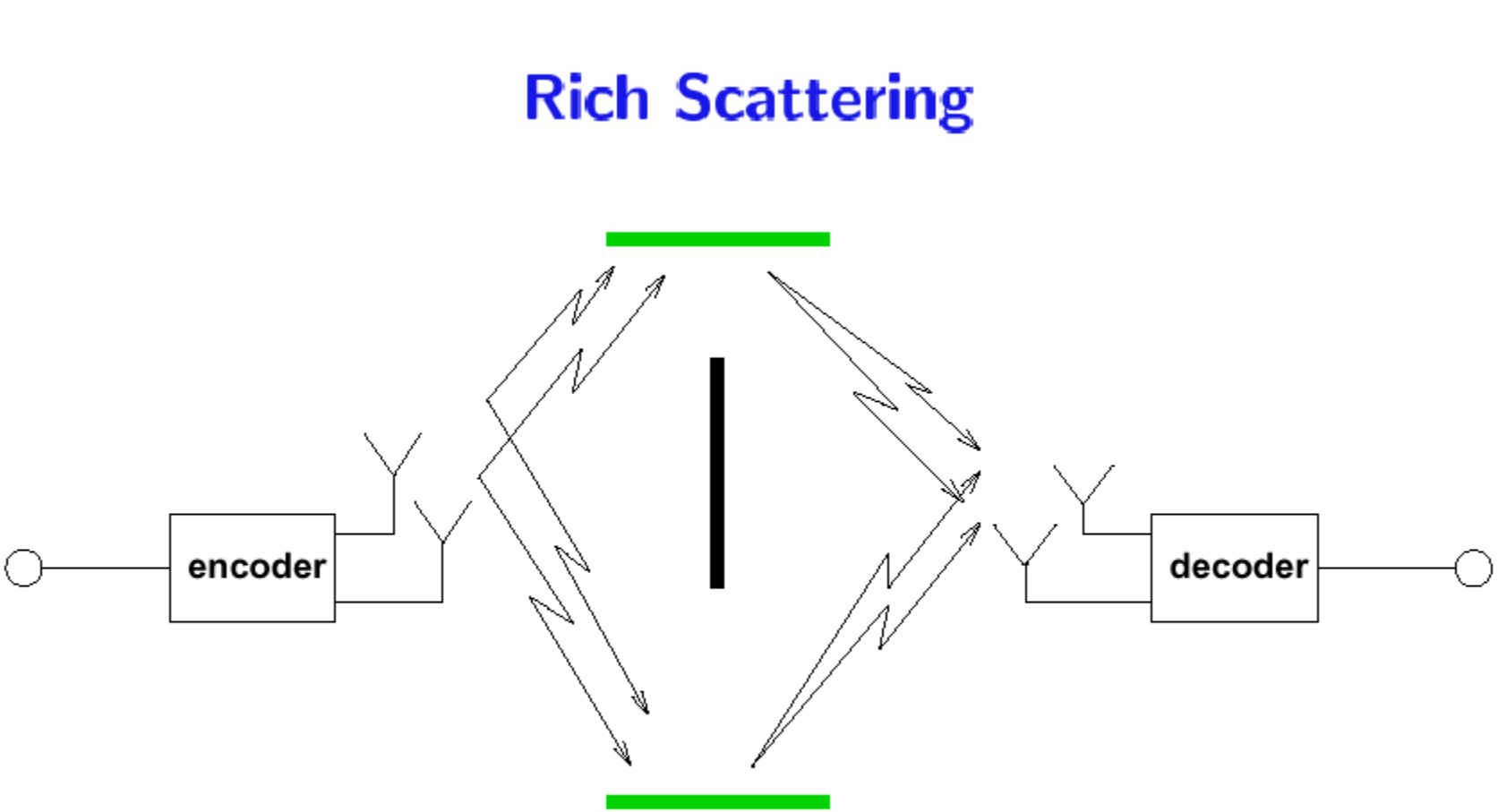
Why is line-of-sight suddenly bad?

Empty Space



Angles between paths are too tiny.

Multipath becomes beneficial!



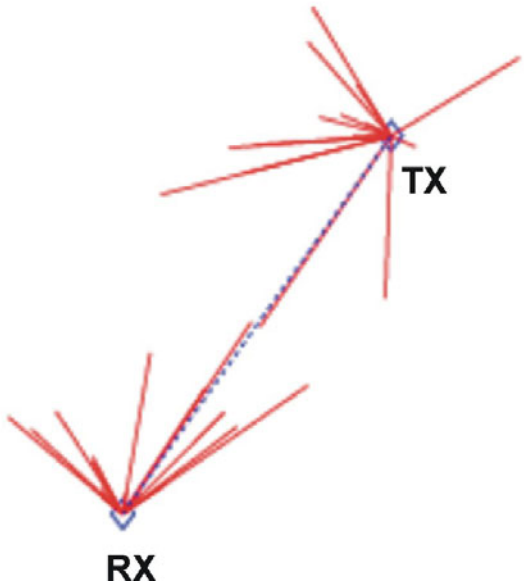
There must be at least as many scatterers as antenna elements.

Part II

Analysis of Channel Measurements

Questions

- How *many* paths exist in a certain environment?
- How much *power* do they carry?
- Can they be *separated*?
- If so, in which *domain*?
- Which are dominant paths?



➡ Propagation directions at ***both*** link ends

Channel measurements during campaign 03/2001

- Outdoor
  - TU-Freihaus, TU-Getreidemarkt, TU-INTHF
  - Suburban area (Vienna, 22nd district)
  - Rural area (Oggau, Burgenland)
  - Salzburgring (High-Speed Mobilestation)
- Indoor
  - Office environment (ftw, INTHF)
  - Factory hall (Warehouse: Zielpunkt)
- Indoor-Outdoor
  - INTHF

Vector Channel Sounder

RUSK ATM Characteristics and Set-up Parameters

- Center frequency 2000 MHz
- Bandwidth 120 MHz

- Sampling rate 320 Ms/s
- MIMO Measurement
- Tx-Rx synchronization via
  - Fiber optic link (for indoor measurements)
  - Rubidium clocks (for outdoor measurements)

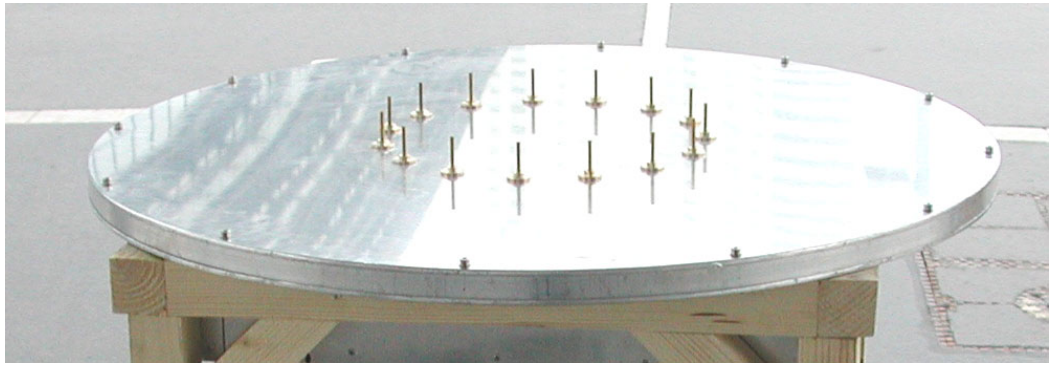
Uniform Linear Receive Array

- 8 patch elements
- Spacing 7.5 cm = $\lambda/2$ at 2 GHz
- Aperture ≈120°
- Multiplexed in time (PIN-Diode Switches)

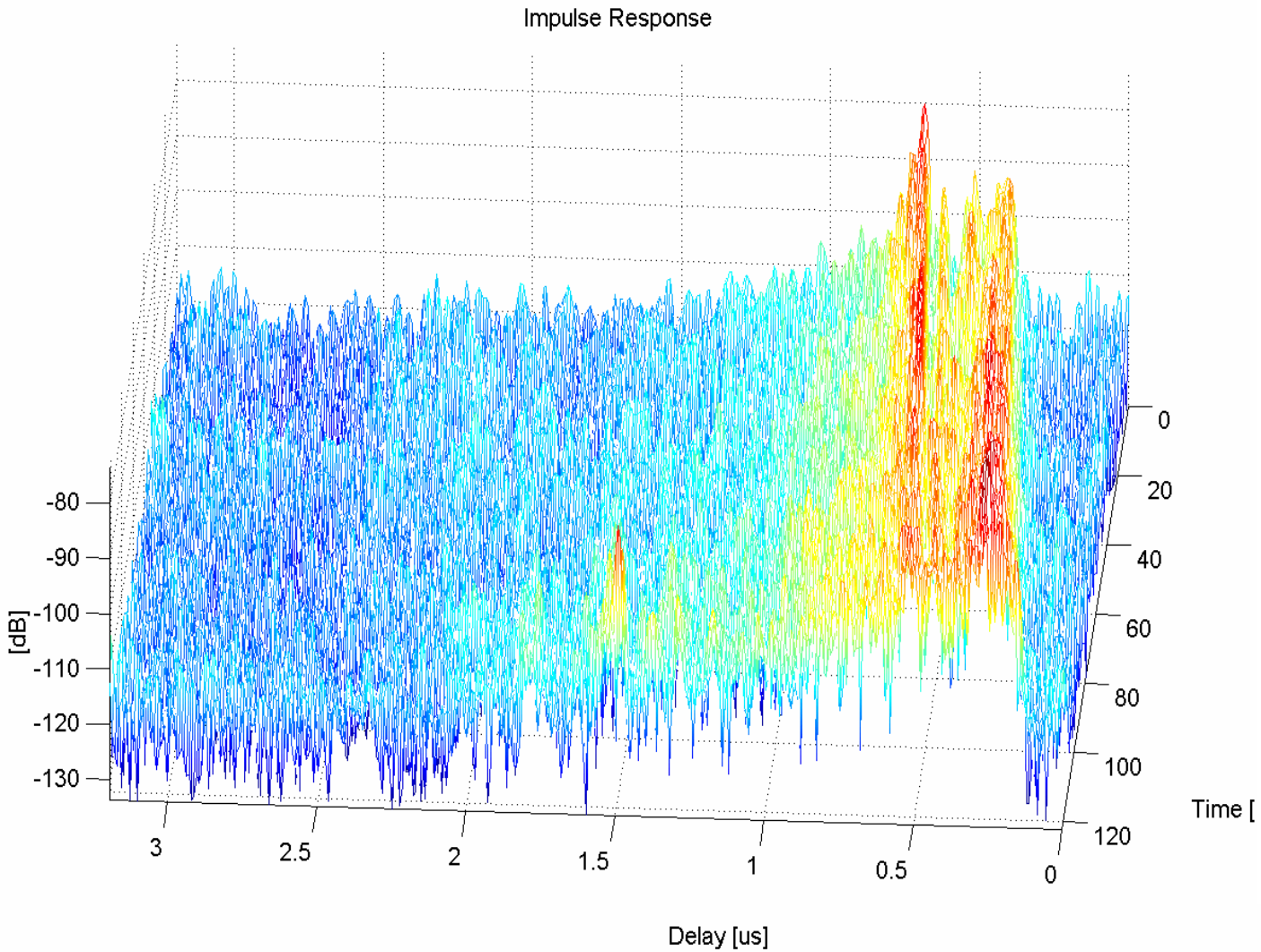
provided by
Deutsche Telekom
T-Nova, Darmstadt, Germany

Uniform Circular Transmit Array

- 15 monopole elements
- Spacing = 0.43 λ at 2 GHz
- Aperture 360° in azimuth
- Aperture 60° in elevation
- Multiplexed in time (PIN-Diode Switches)



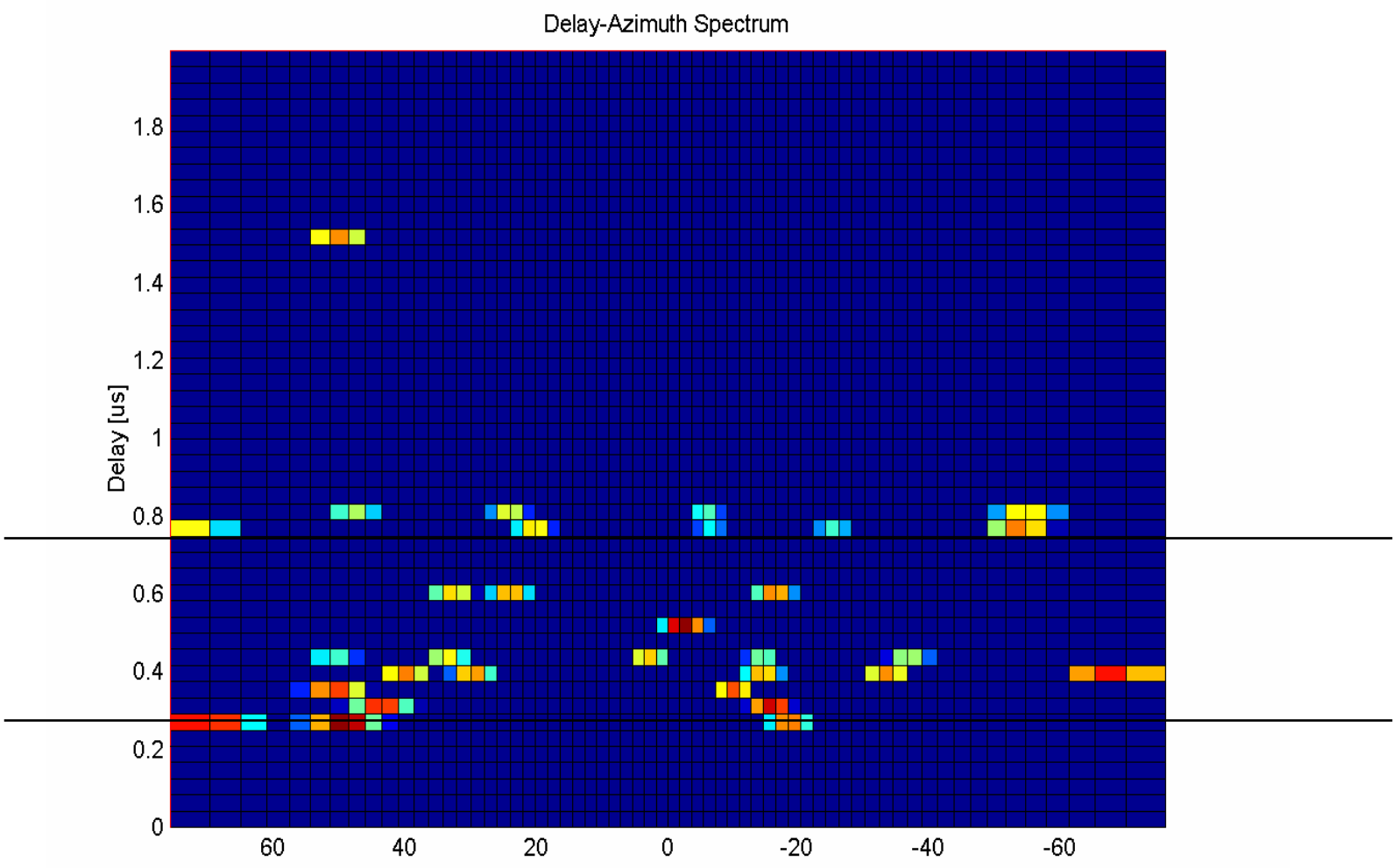
Example Outdoor



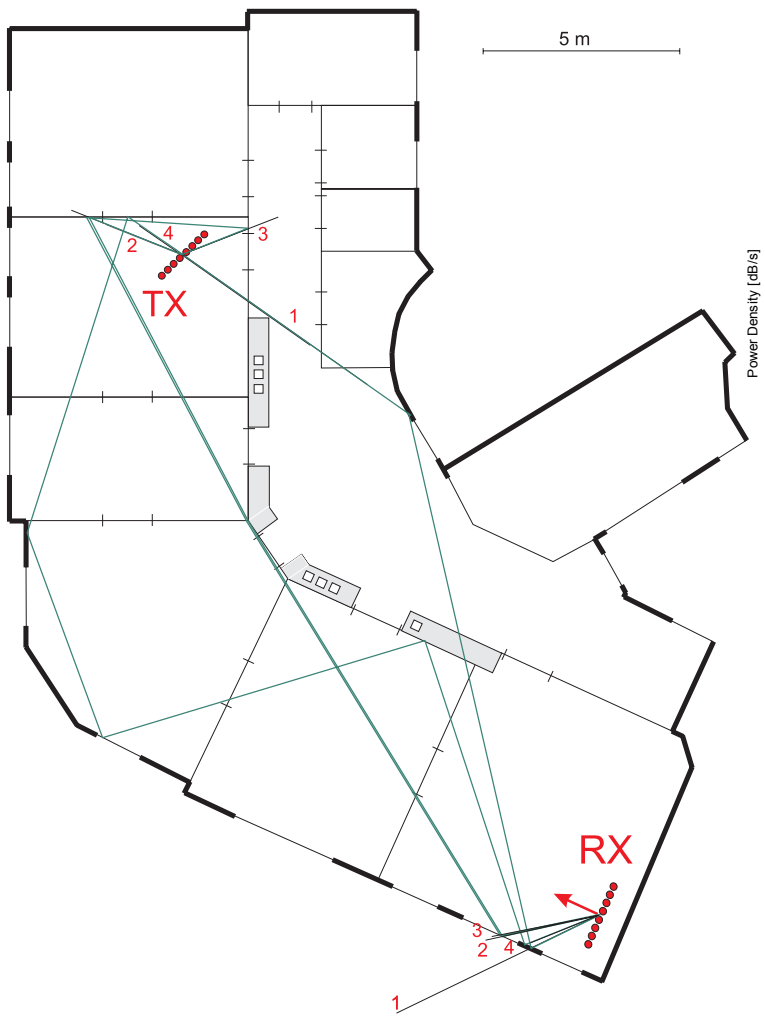
SIMO and MIMO measurements

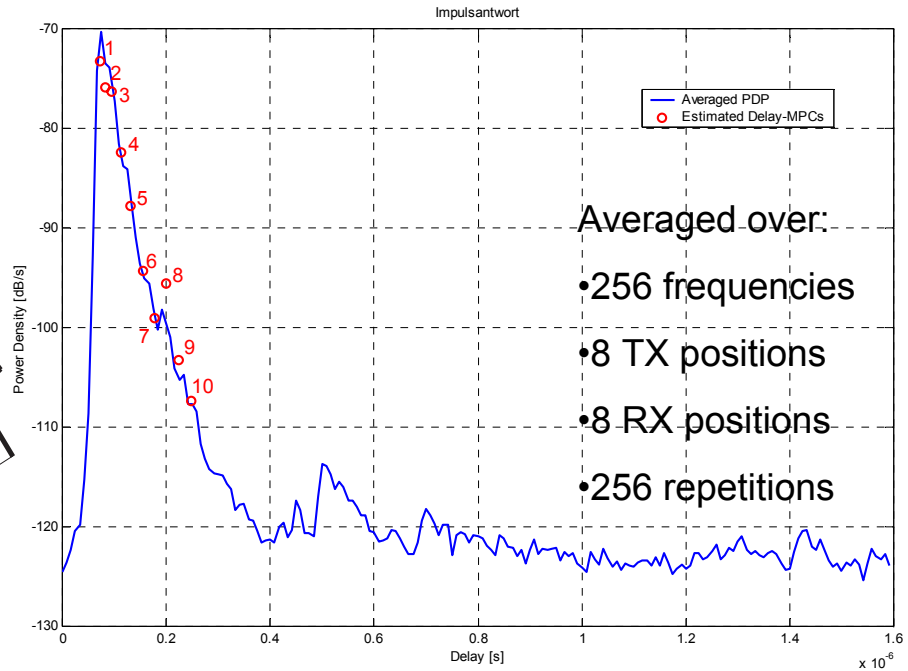
- SIMO enables DoA estimation
  - Resolution of paths in time-delay and DoA
- MISO enables DoD estimation
  - Resolution of paths in DoD and time-delay
- MIMO enables *joint* DoA-DoD estimation
  - Complete characterization of channel feasible

Example Outdoor, Street Canyon



Example: Indoor Office





	τ [ns]	DOA [°]	DOD [°]
1st path	73,2	44	-11
2nd path	82,5	32	147
3rd path	95,4	31	-66
4th path	113,2	40	170

M. Steinbauer, ISSSE'01, Tokyo 2001.

Indoor Office (cont'd)

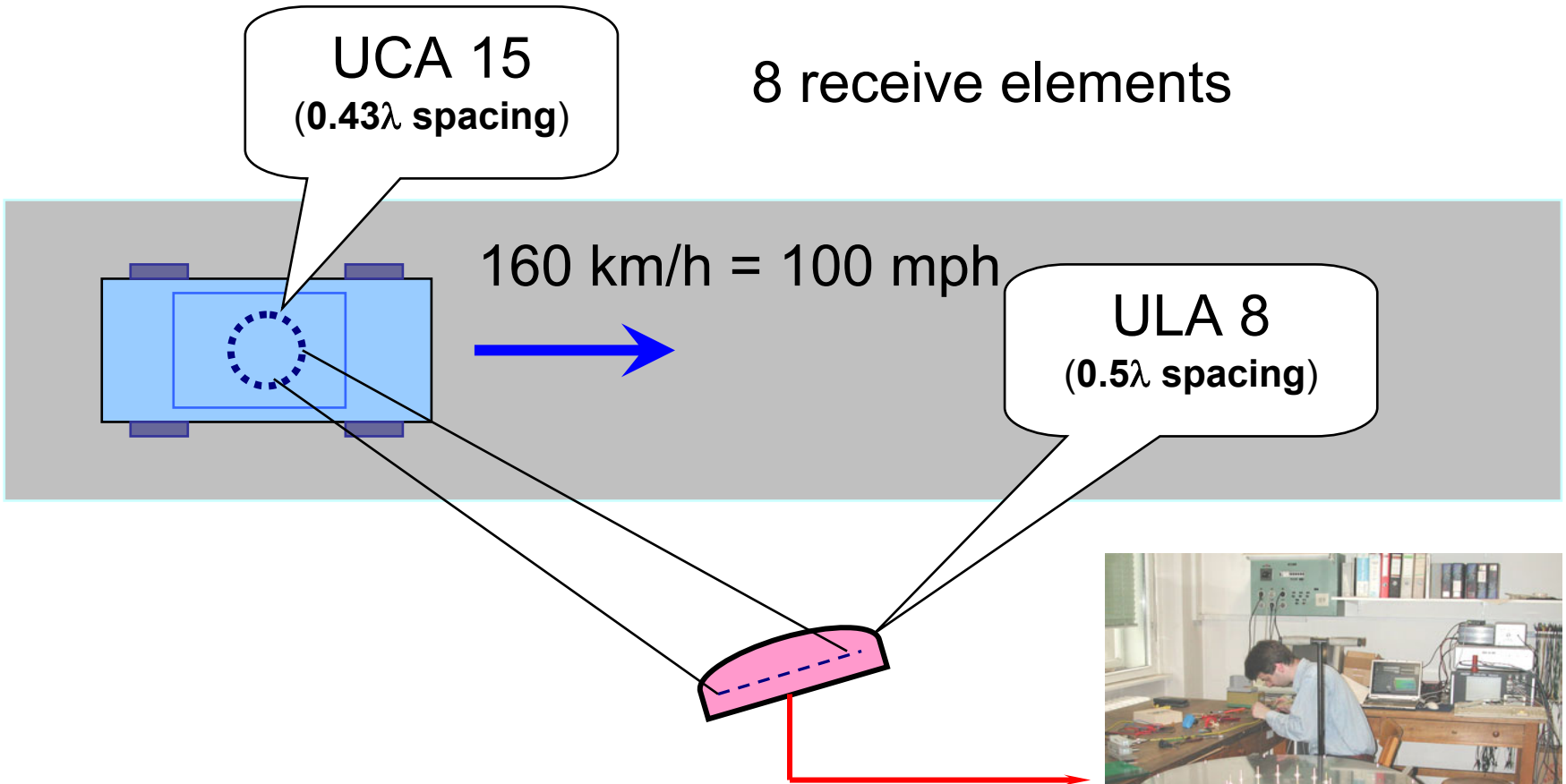
- In our office, we seem to have just around 6 relevant scatterers.

- Implication: It does not make much sense to deploy a wireless MIMO system with more than 6 antenna elements on both sides.

MIMO measurement at high speed

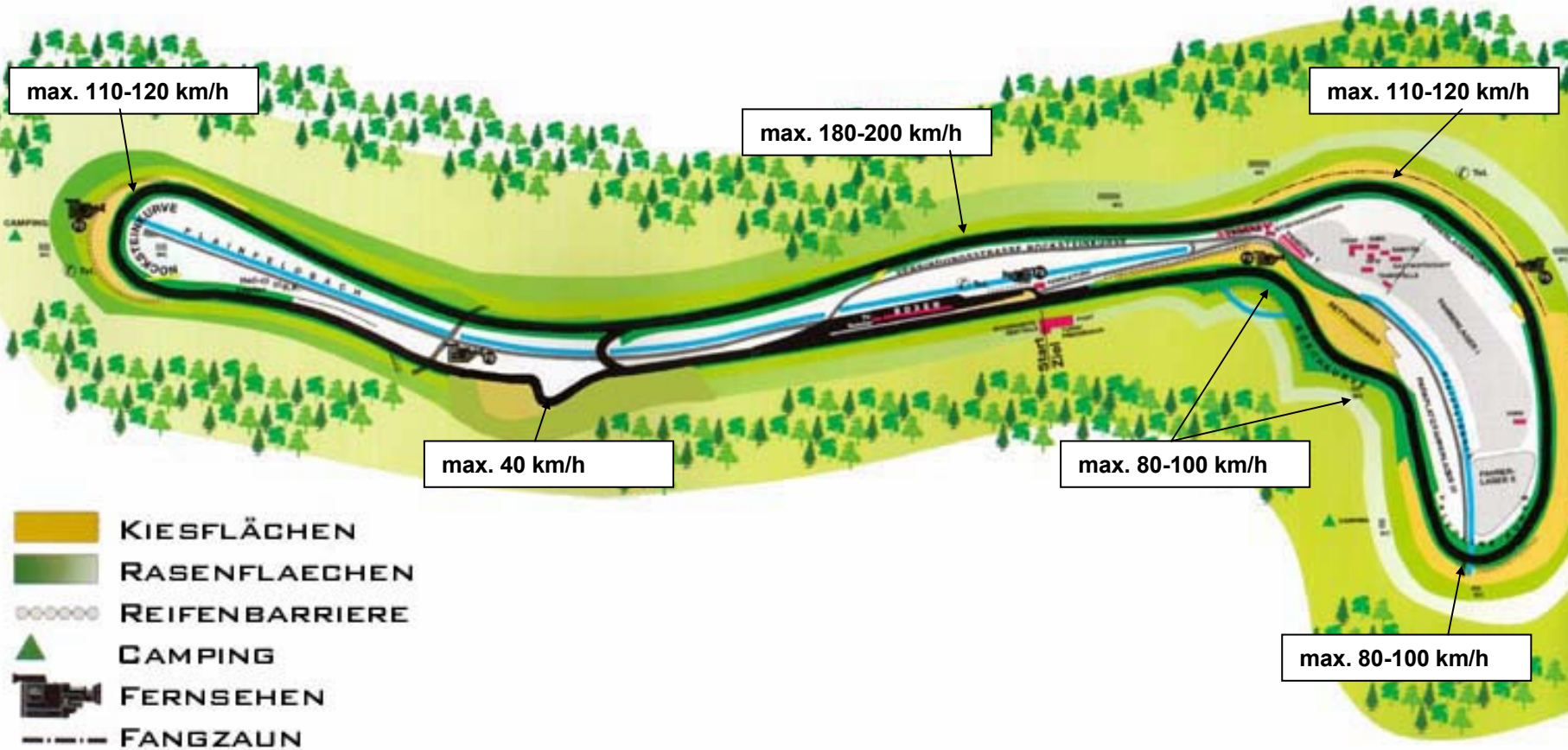
15 transmit elements

8 receive elements



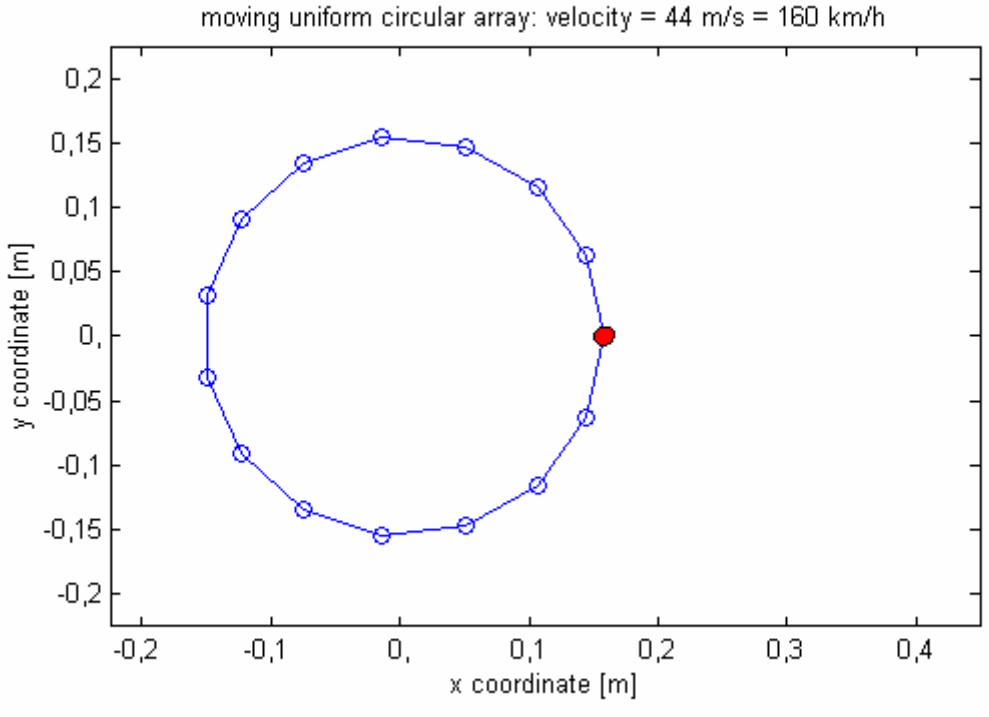
SALZBURGRING

circulation clockwise, max. speeds achieved by „good drivers“ with standard cars according to information given by Salzburgring officials (8.1.2001)



Effective array geometry

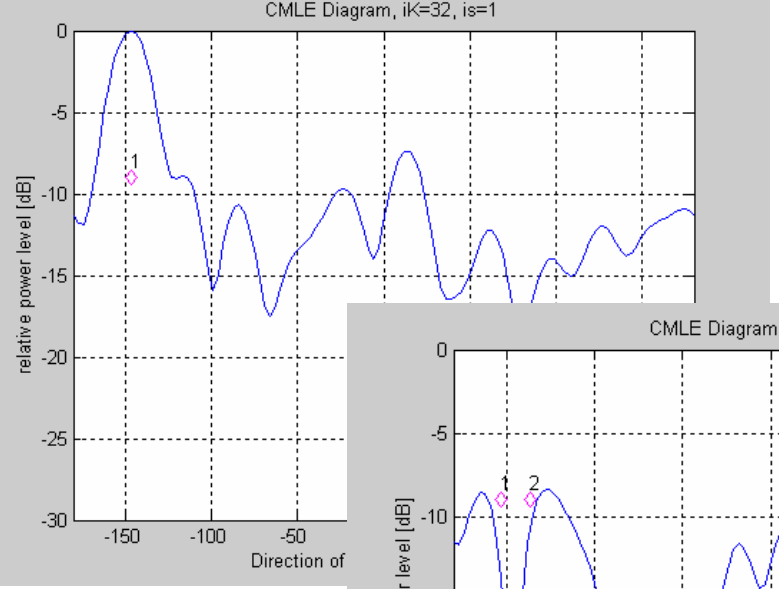
Not circular!

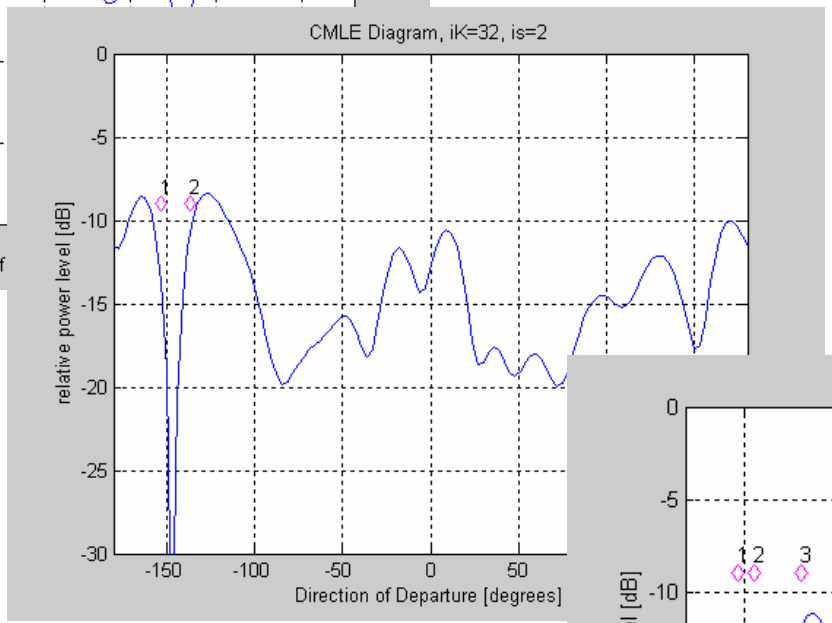


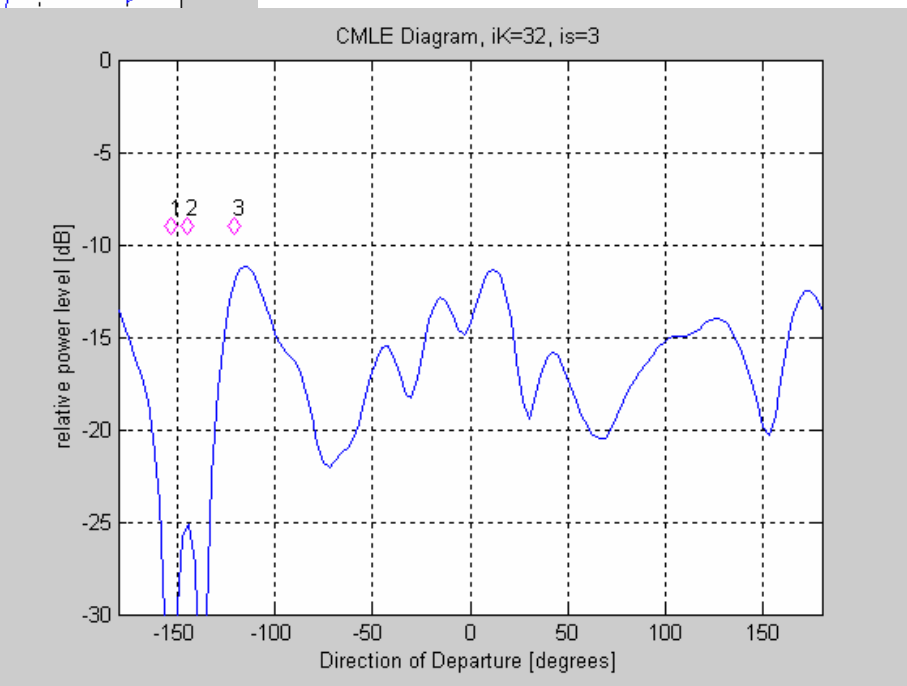
Parametric Channel Matrix Model

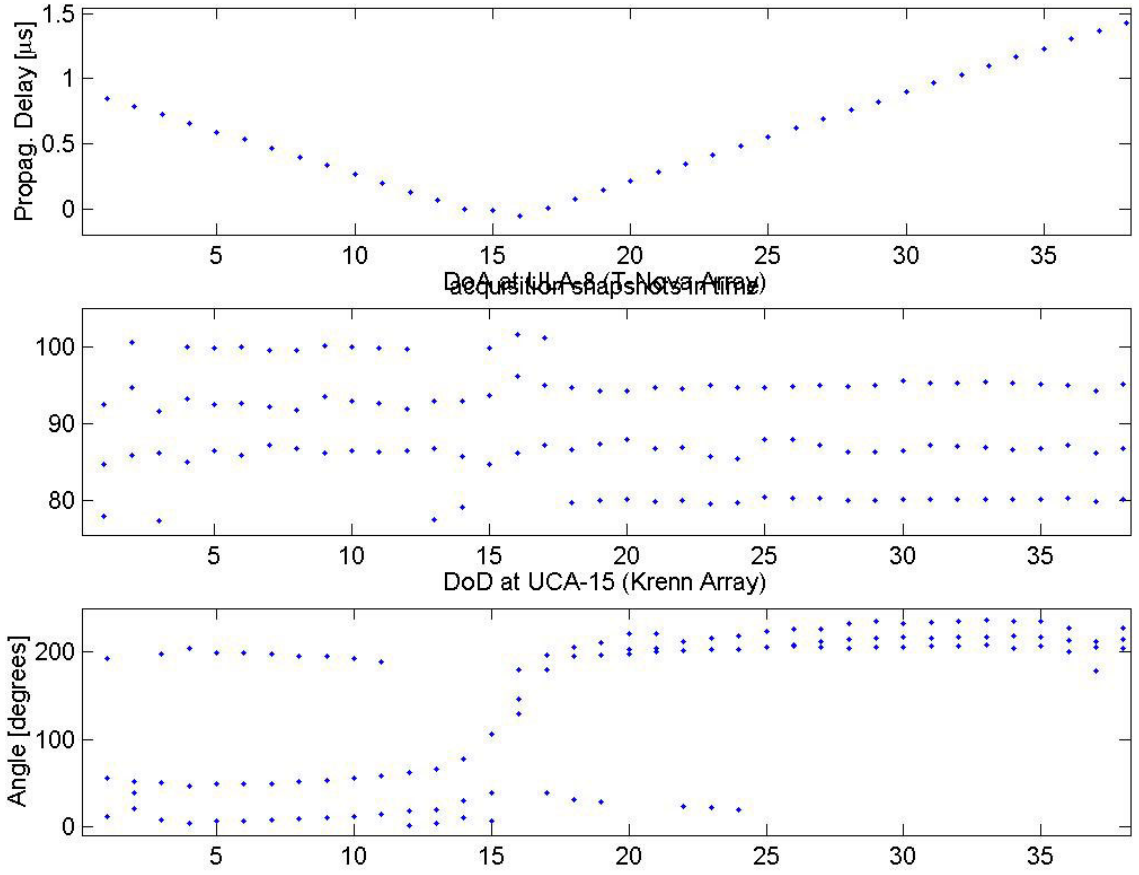
- $\boldsymbol{H}$ depends on environment:
  - number of relevant scatterers
  - locations of relevant scatterers
  - cross sections of relevant scatterers
  - etc.
- $\boldsymbol{H}$ depends on Tx antenna element positions
- $\boldsymbol{H}$ depends on Rx antenna element positions

- Non-linear parameters summarized in vector $\boldsymbol{\theta}$


CMLE Diagram, iK=32, is=1
relative power level [dB]
0
-5
-10
-15
-20
-25
-30
1
-150
-100
-50
Direction of


CMLE Diagram, iK=32, is=2
relative power level [dB]
0
-5
-10
-15
-20
-25
-30
1
2
-150
-100
-50
0
50
Direction of Departure [degrees]


CMLE Diagram, iK=32, is=3
relative power level [dB]
0
-5
-10
-15
-20
-25
-30
1
2
3
-150
-100
-50
0
50
100
150
Direction of Departure [degrees]

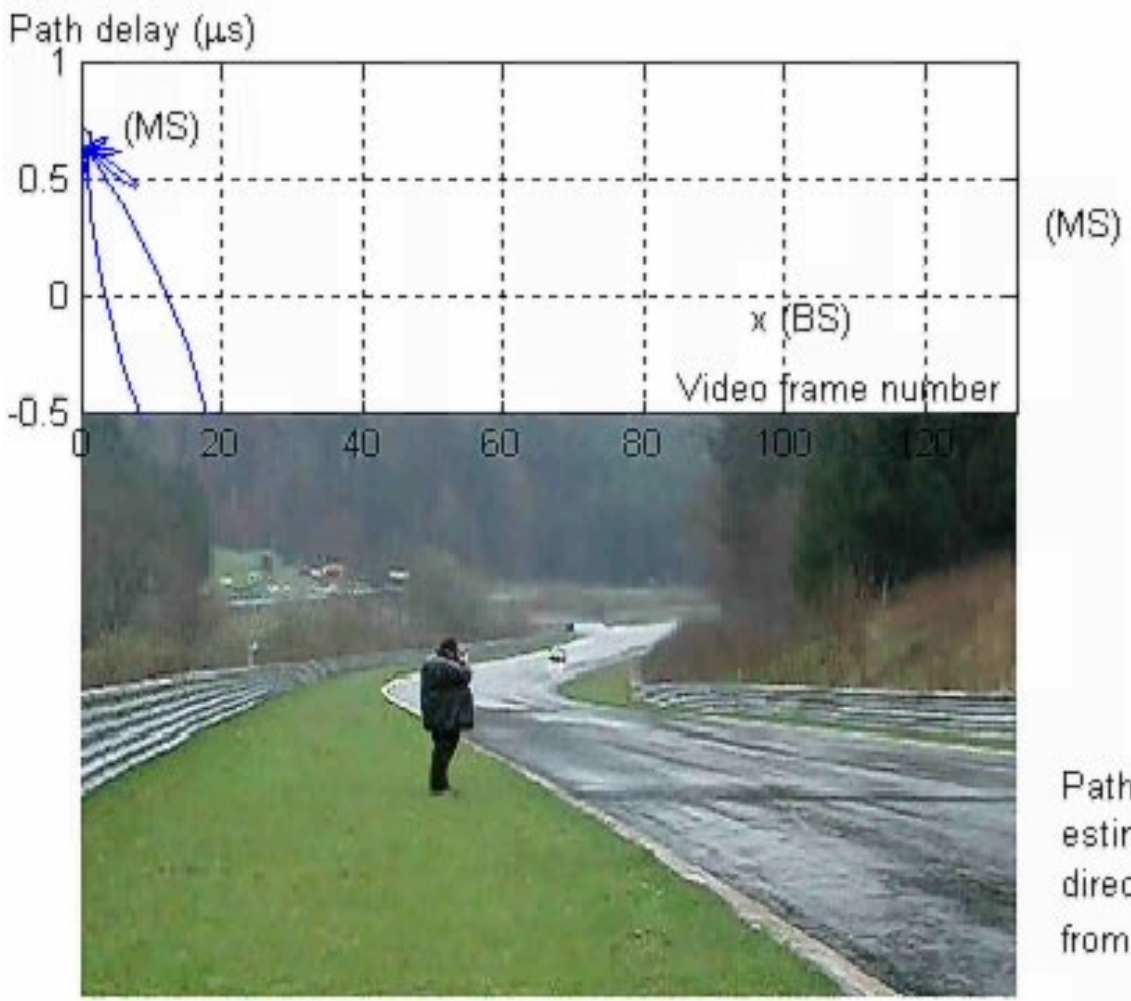


WPMC'01, Aalborg, Sep. 2001.

Transmit Beamforming: Angular Water-filling

Path delay and estimated dominant directions of departure from mobile array

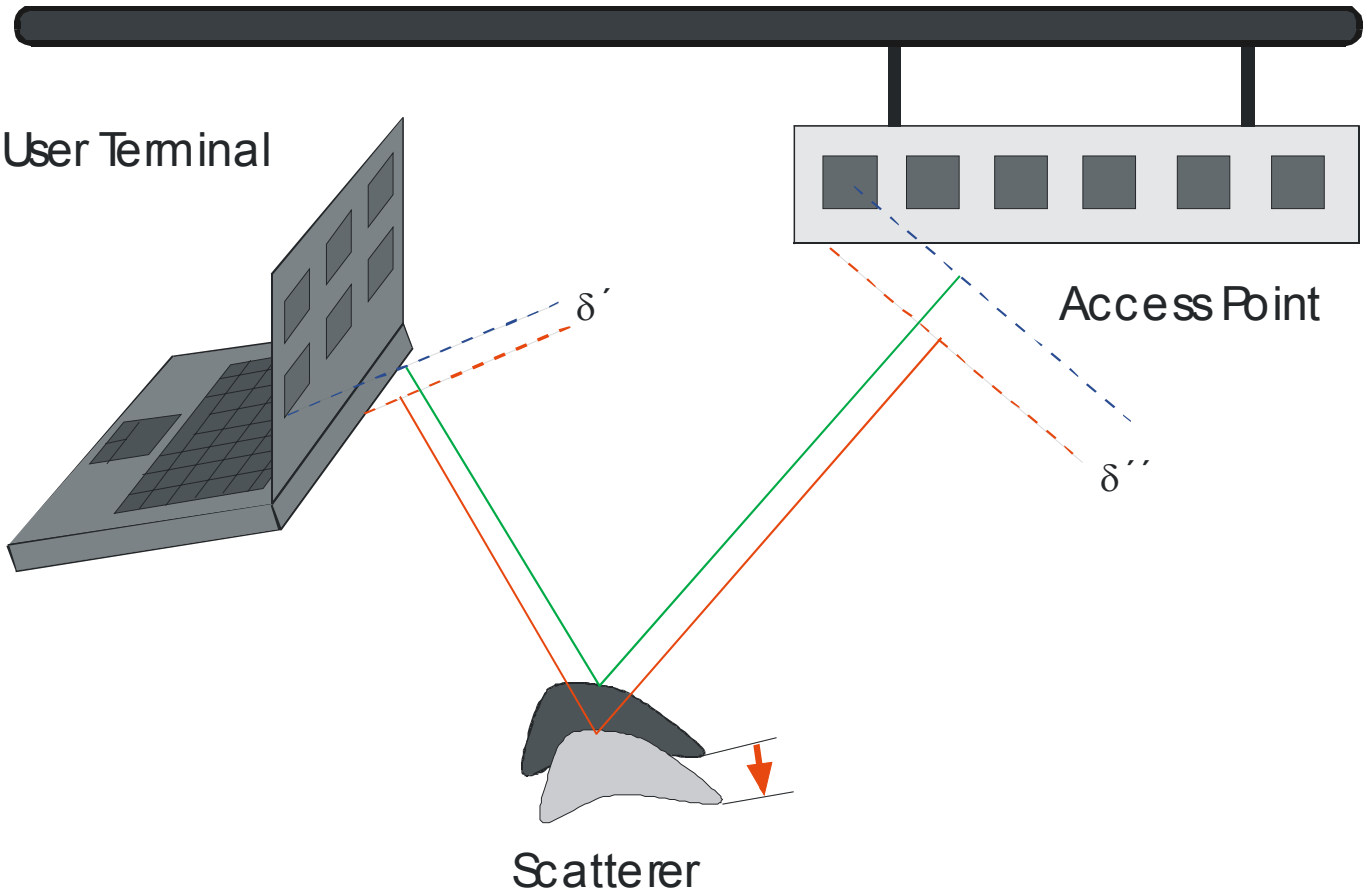
Total radiative power profile



Path delay and estimated dominant directions of departure from mobile array

Andy Molisch's idea: Evaluation of MIMO Capacity from Measurements

- virtual displacement of scatterers

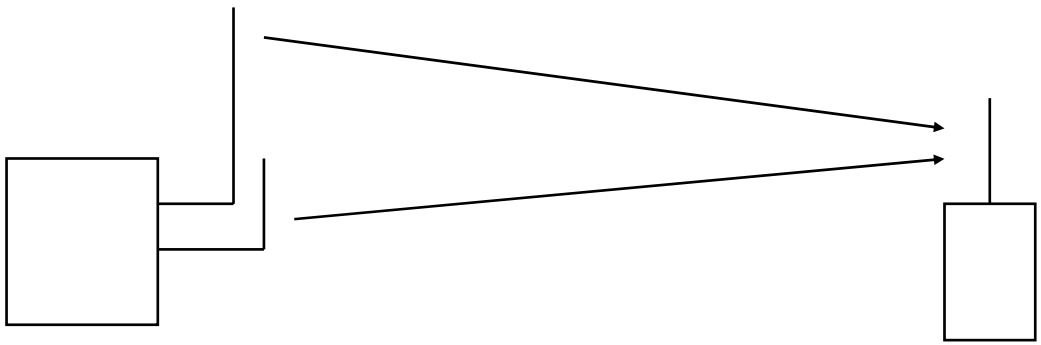


Part III

Alamouti's Space-Time Diversity Code

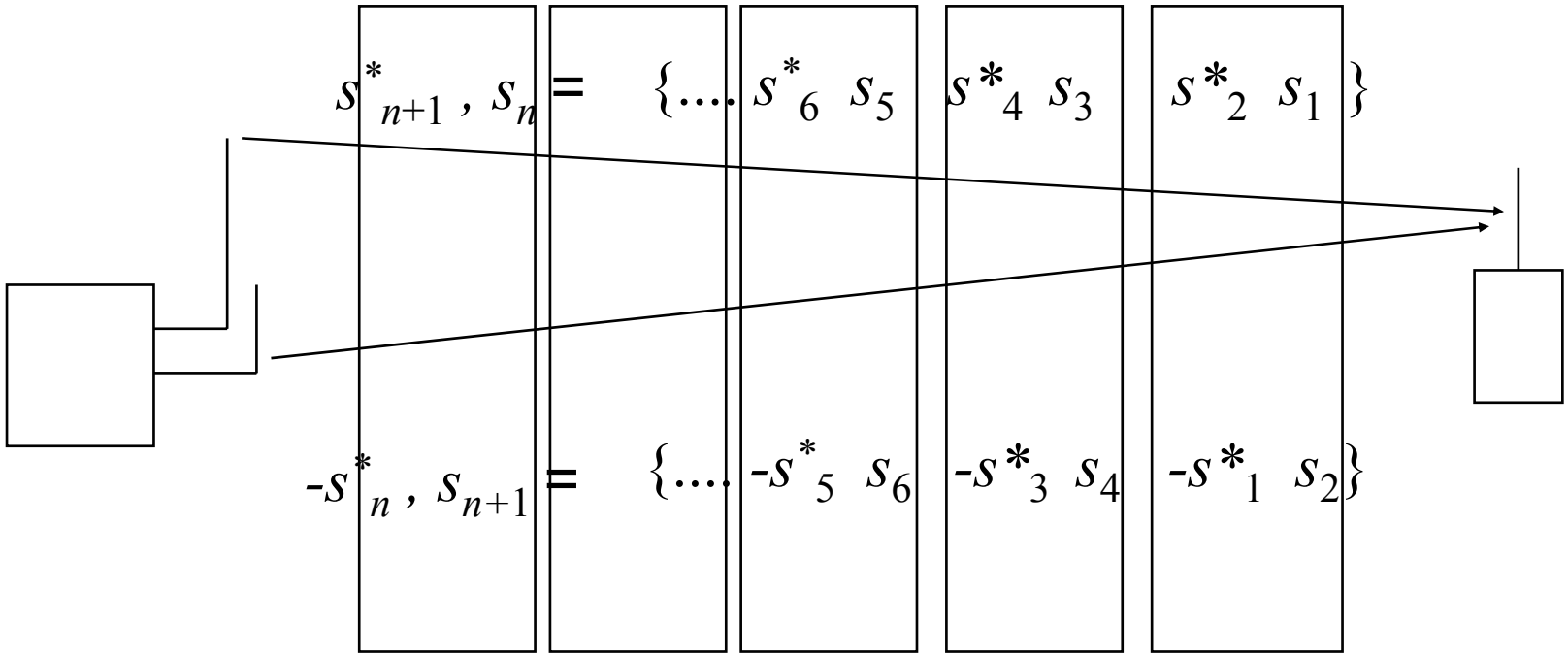
Downlink

- Transmit Diversity (2 Tx, m Rx)
  - Open-loop mode: Alamouti ST-code
    - diversity gain only: no array gain



UE needs to estimate the channels from both Tx antennas:

Alamouti ST-Diversity Code



Received sequence at UE

$$\begin{pmatrix} y_n \\ y_{n+1}^* \end{pmatrix} = \begin{pmatrix} h_1 & h_2 \\ -h_2^* & h_1^* \end{pmatrix} \begin{pmatrix} s_n \\ s_{n+1} \end{pmatrix} + \begin{pmatrix} u_n \\ u_{n+1}^* \end{pmatrix}$$

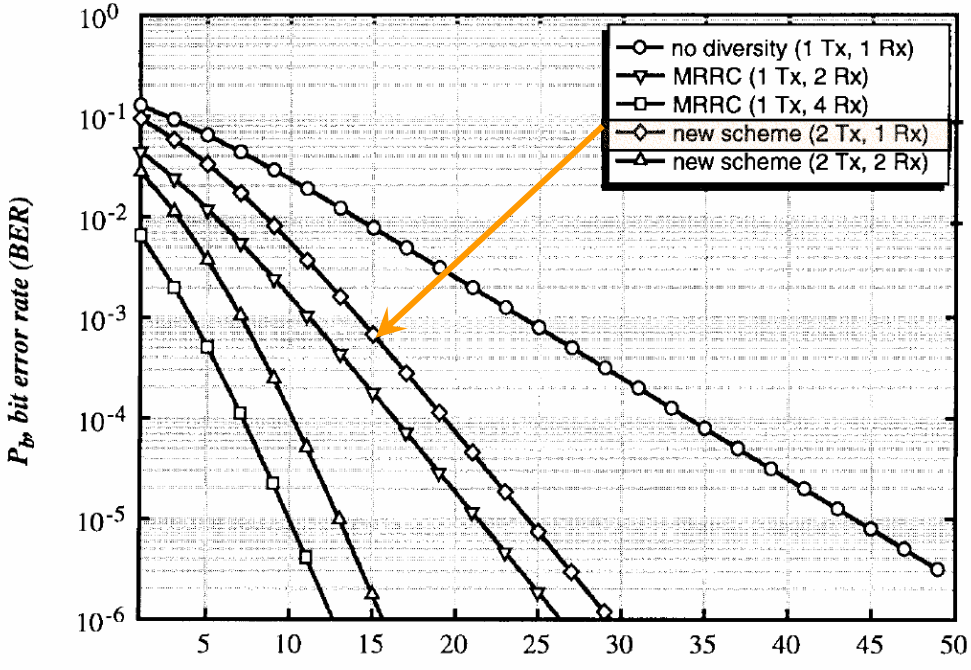
$$\boldsymbol{y}(n) = \boldsymbol{H}\boldsymbol{s}(n) + \boldsymbol{u}(n)$$

2x2 channel matrix is unitary

Zero-forcing:

$$\hat{s}(n) = \frac{1}{|h_1|^2 + |h_2|^2} \boldsymbol{H}^H \boldsymbol{y}(n)$$

Example: Alamouti Scheme (1)



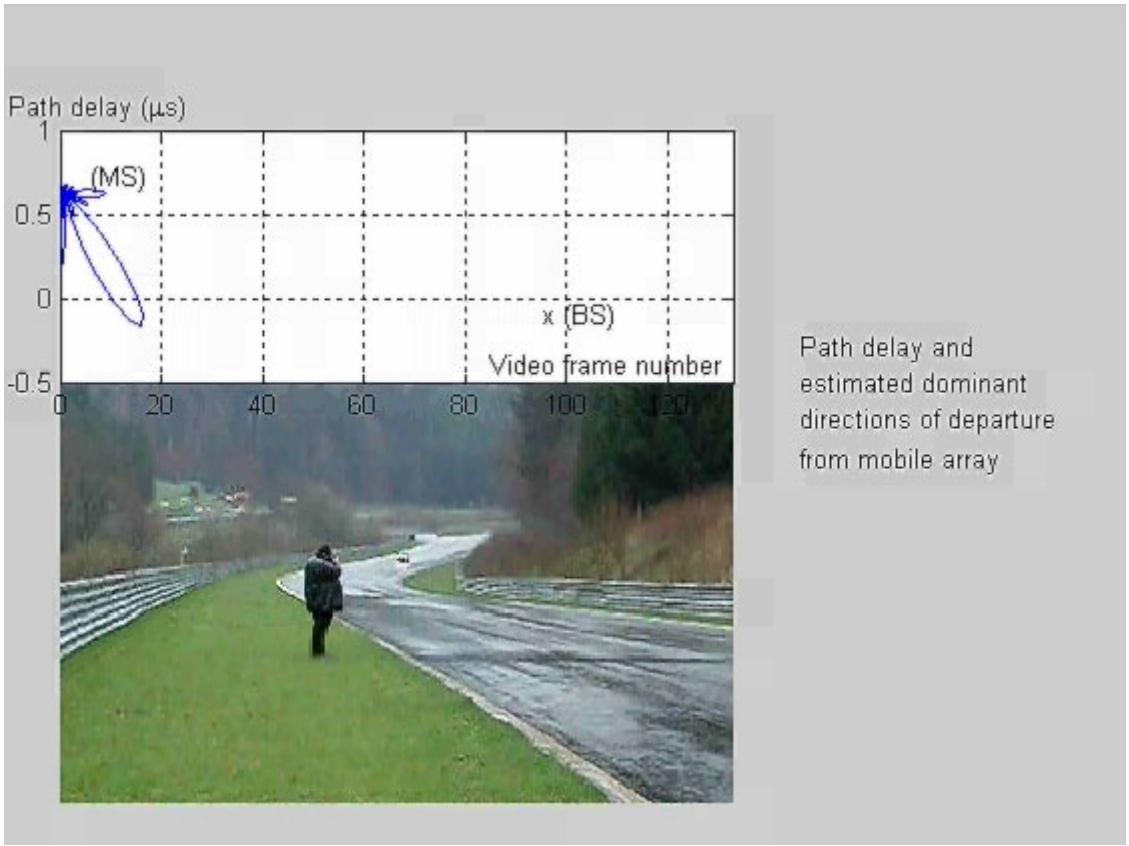
The BER performance comparison of coherent BPSK with MRRC and two-branch transmit diversity in Rayleigh fading

Alamouti, *IEEE J. Sel. Ar. Comm.* **16**(8):1451-1458, Oct. 1998

Summary

- Wireless MIMO channel provides a significant capacity boost, but ...
- the capacity is strongly dependent on the multipath structure of the radio environment
- Simple implementations are part of 3G (UMTS)
- The transmitter needn‘t know the channel
- Good ST-codes are known

Thank you



Path delay and estimated dominant directions of departure from mobile array