MIMO Propagation Channel Modeling

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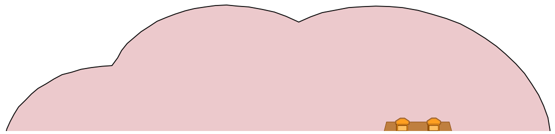
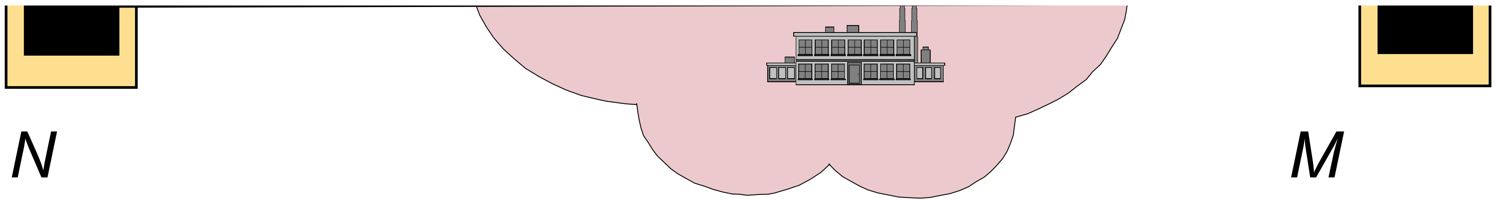
TU WIEN

The Multiple-Input Multiple-Output (MIMO) Channel



A MIMO system consists of **several antenna elements** at both transmitter and receiver, plus **adaptive signal processing**; this combination exploits the **spatial** dimension of the **radio propagation** channel.



Goals of MIMO

Interference Suppression

Array Gain

- increase receive power
- beamforming

But will the propagation channel support what you devise?

Spatial Multiplexing

- multiply data rates

Diversity

- mitigate fading

MIMO Channel Matrix *H*

Consists of *MxN* impulse responses h_{ij} of transmit antenna j to receive antenna i

$$\mathbf{H}(t,\tau,\varphi)=\begin{bmatrix} h_{11}(t,\tau,\varphi) & h_{12}(t,\tau,\varphi) & \cdots & h_{1N}(t,\tau,\varphi) \\ h_{21}(t,\tau,\varphi) & h_{22}(t,\tau,\varphi) & \cdots & h_{2N}(t,\tau,\varphi) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1}(t,\tau,\varphi) & h_{M2}(t,\tau,\varphi) & \cdots & h_{MN}(t,\tau,\varphi) \end{bmatrix}$$

Time t

Signal delay τ

Angular dependence φ

Outline

Modeling Philosophies

- random or deterministic channel?
- individual multipath or MIMO matrix?

MIMO Measurements

Two Models

Deterministic vs random MIMO channels

In general, the MIMO channel is *random*.

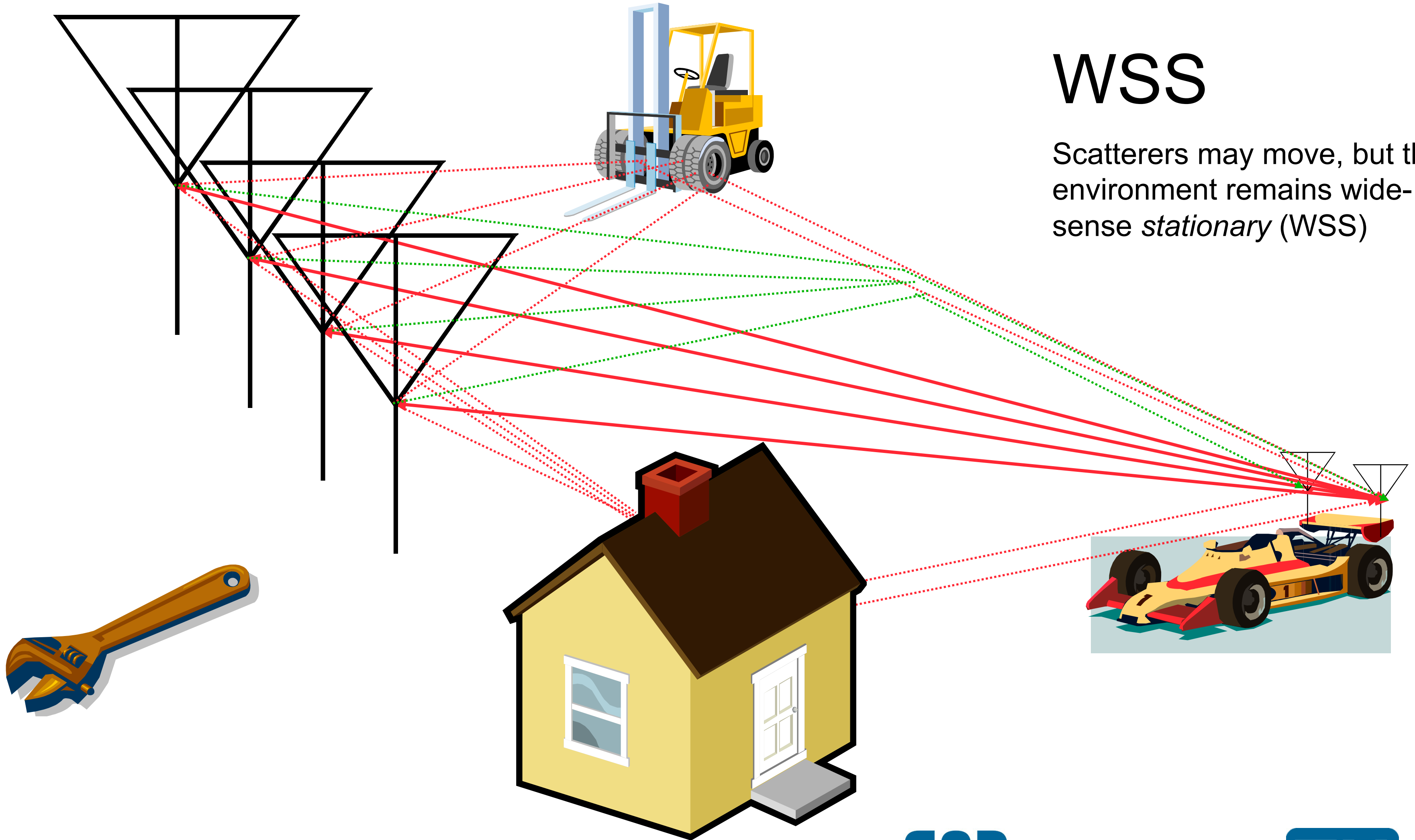
A snapshot of the MIMO channel is a single *deterministic* realization of the random MIMO channel.

Deterministic and random MIMO channels have to be treated quite differently!

We model the channel for network planning and deployment: as deterministic, site-specific – by Maxwell, UTD,...

We model the channel for system design and testing: as random, scenario-specific – by statistics (distribution & moments)

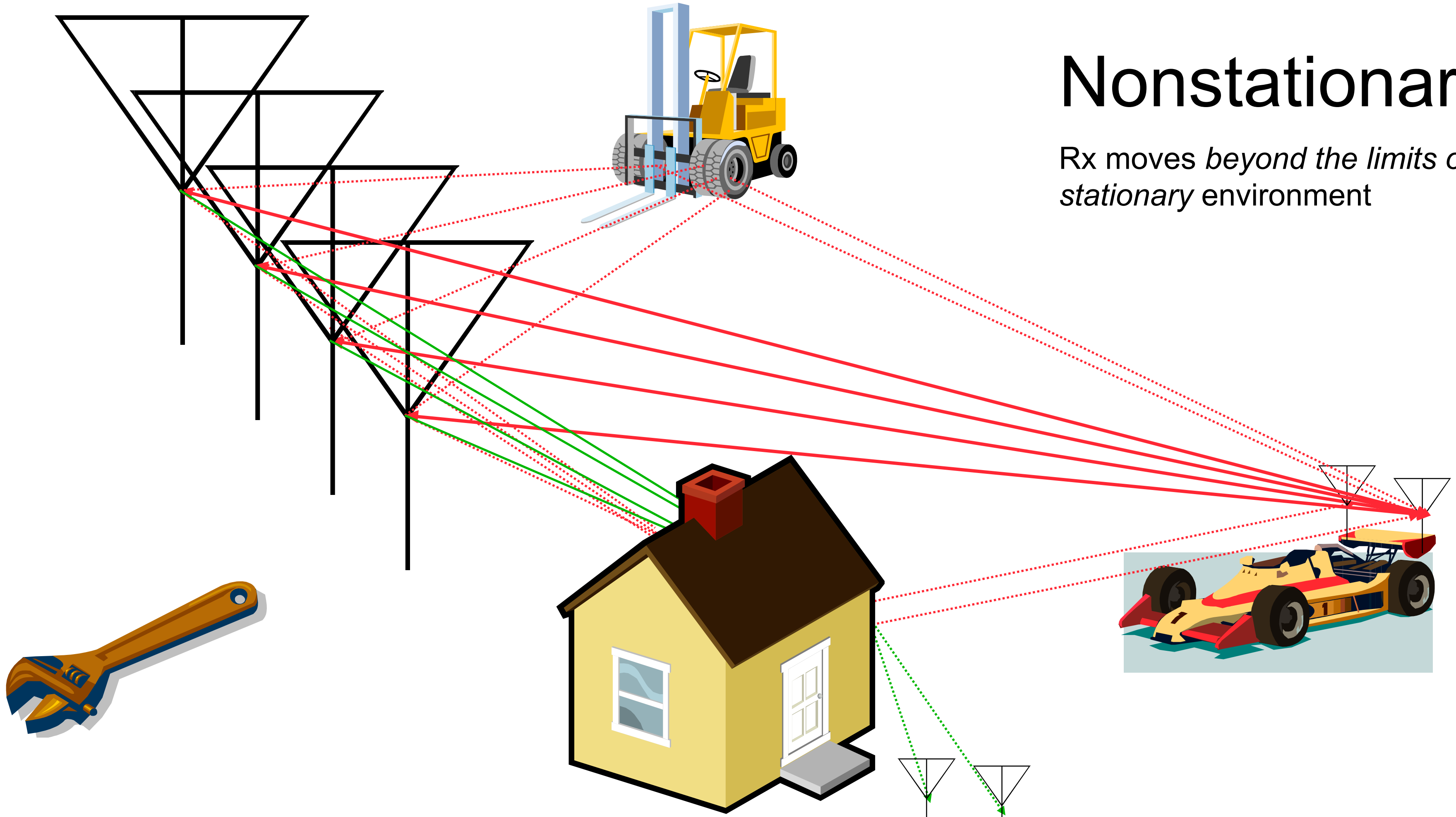
Sources of MIMO Randomness

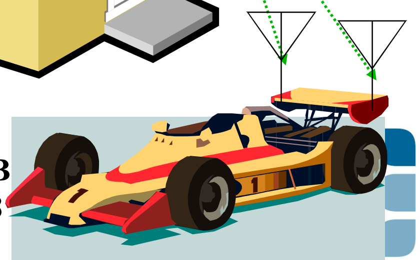


WSS

Scatterers may move, but the environment remains wide-sense *stationary* (WSS)

Sources of MIMO Randomness





Nonstationary

Rx moves *beyond the limits of a stationary* environment

Common mistakes in MIMO channel modeling

- Make ONE model from measurements in different, albeit stationary scenarios
- Make ONE model, believed to be stationary, from measurements in non-stationary scenario

(Correction due to J.-C. Oestges' question)

- AVERAGE channel that never exists

What to model?

A. Electromagnetic propagation in detail => multipath

scattering objects
path loss
(de-)polarization, XPD
angular distribution
temporal evolution
Doppler
… and eventually ***H***, the MIMO channel matrix

B. MIMO channel matrix ***H*** directly

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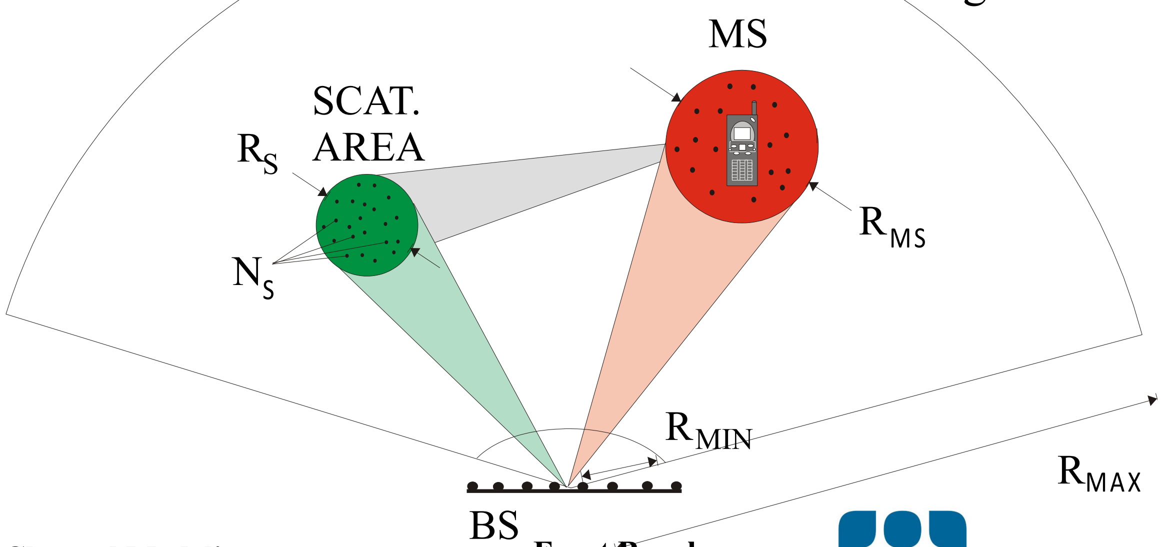
Geometry-based stochastic channel modeling (GSCM)

- If A: deterministic ray-tracing or random scattering objects?
- Compromise: **G**eometry-based **S**tochastic **C**hannel **M**odeling (GSCM)

- Select sample scenarios
- Prescribe *probability density function* of near-by scatterers
- Prescribe regions of distant scatterers such as high-rise building groups or mountains (fixed in space)
- Simple ray tracing with specular reflection
- Excellent for time evolution and interference modeling



Outline

Modeling Philosophies

MIMO Measurements

- massive postprocessing
- double-directional channel
- clusters
- diffuse multipath

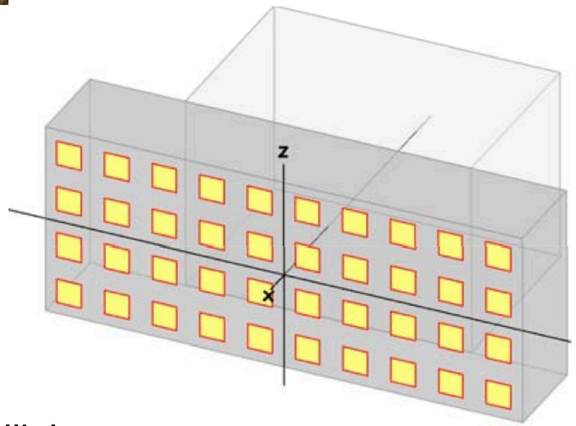
… and common mistakes

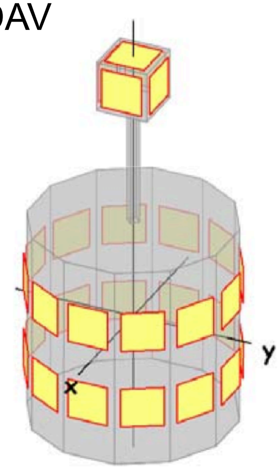
Two Models

Measurement equipment

Elektrobit Oy

TU Ilmenau & MEDAV



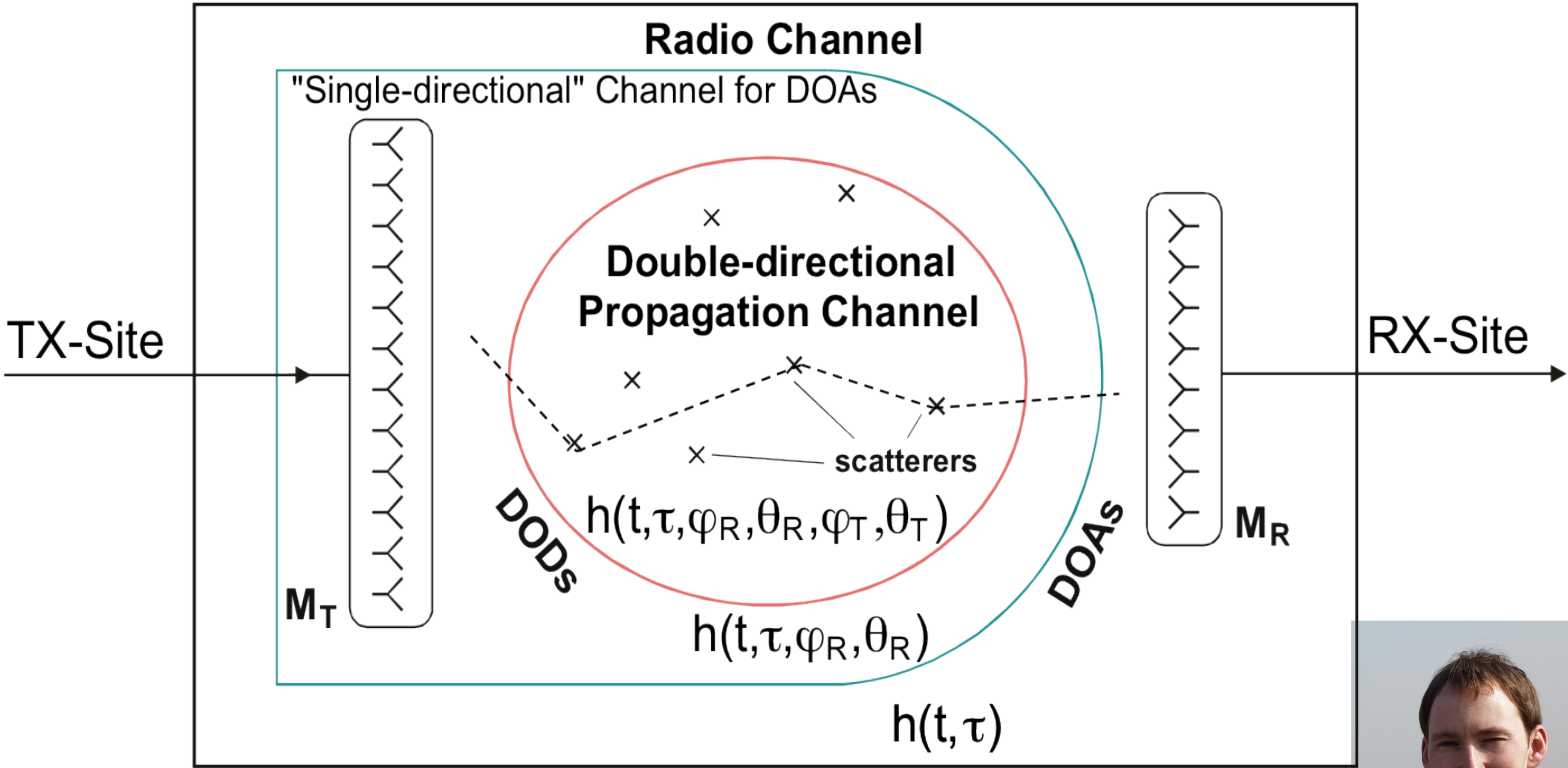


Kimmo Kalliola
Helsinki University of Technology

Superresolution Estimation of Multipath Components

- Massive signal processing
- Direction finding by
- ESPRIT, MUSIC, SAGE, RIMAX,...

The Double-directional Propagation Channel

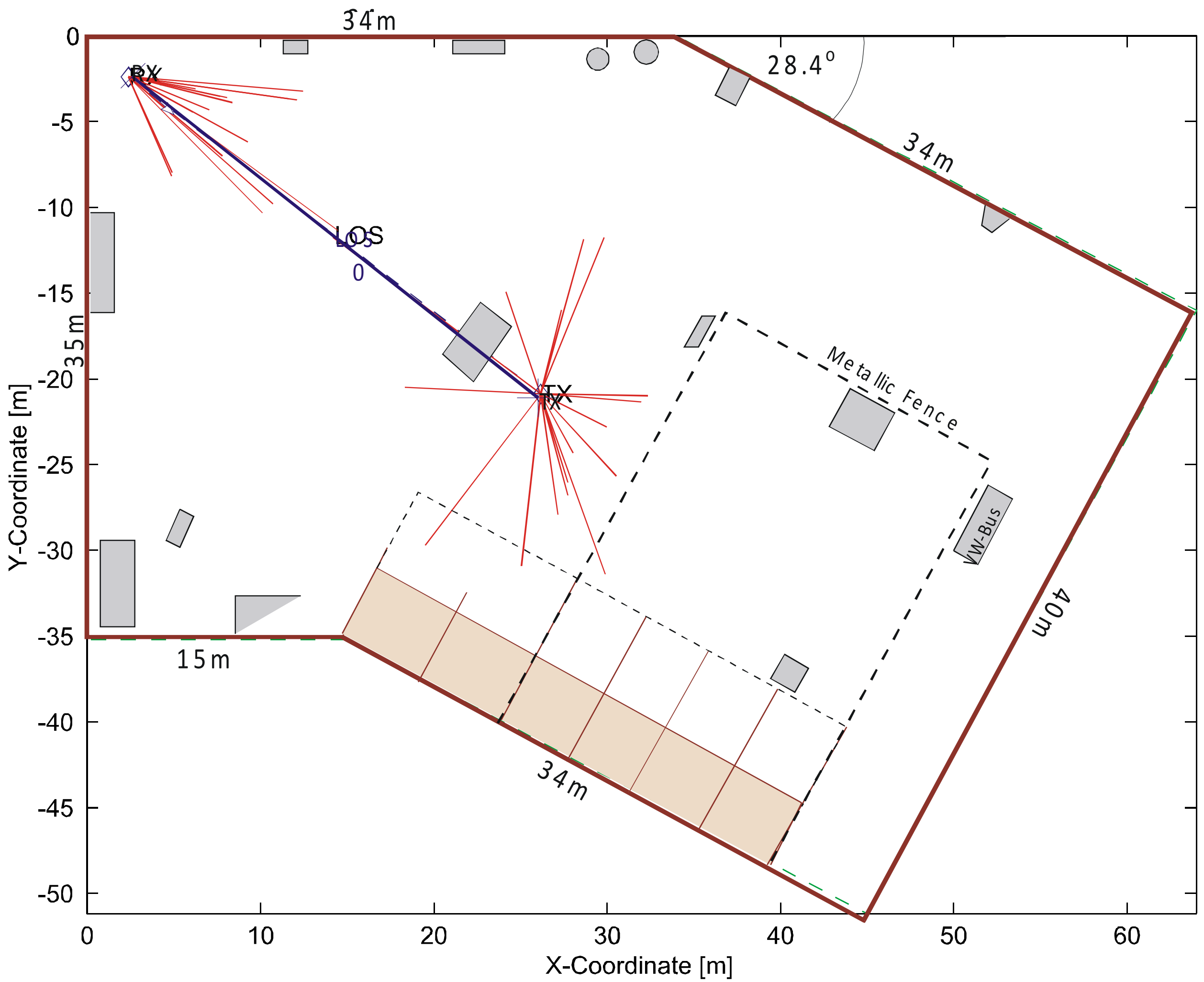


M. STEINBAUER, COST259 TD(98)027, Feb.1998, Berne, Switzerland
M. STEINBAUER et al., IEEE VTC-2000-Spring, Tokyo, May 15-18, 2000
M. STEINBAUER et al., IEEE AP Magazine, August 2001, pp. 51-63

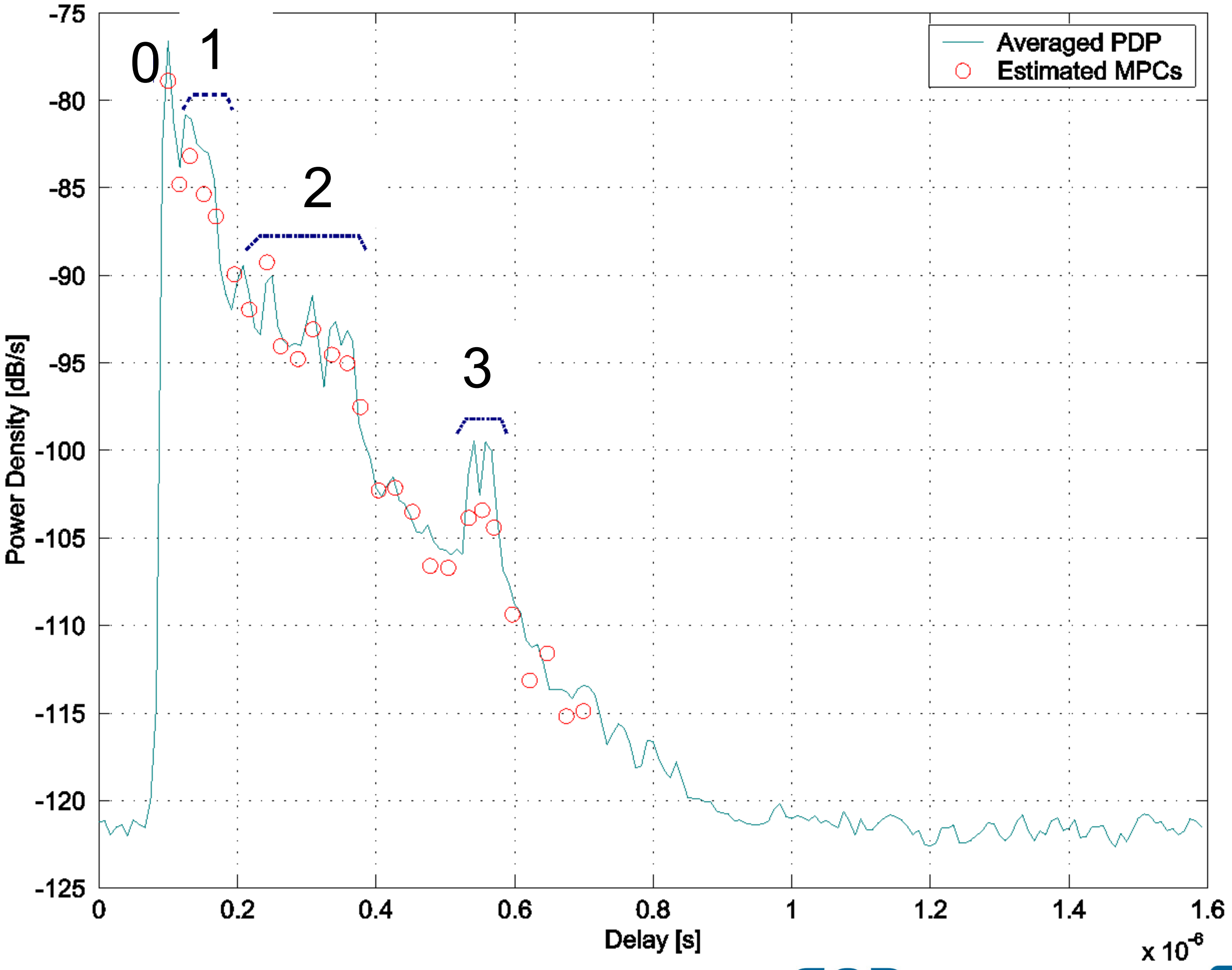
Backyard - NLOS

Technische Universität Ilmenau, Germany

Backyard - OLOS: Tracing Individual Multipath

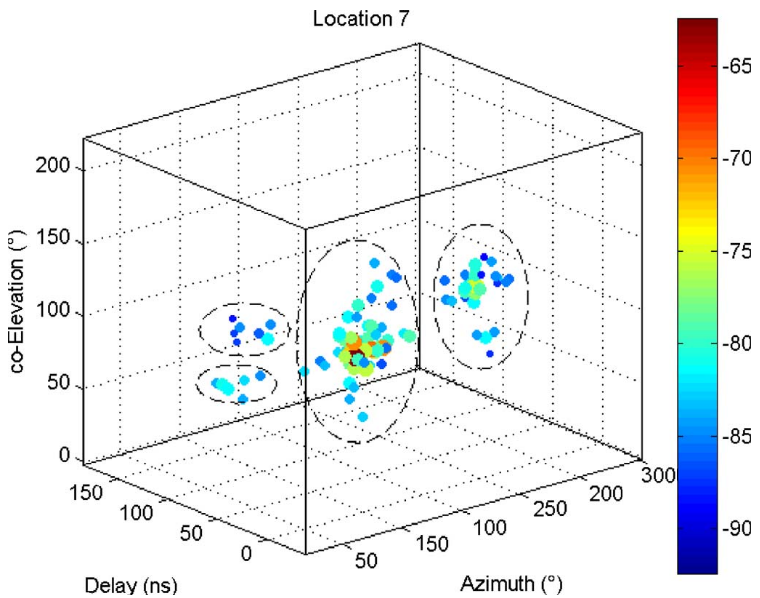


Backyard - OLOS: Power Delay Profile



Observed MIMO effects

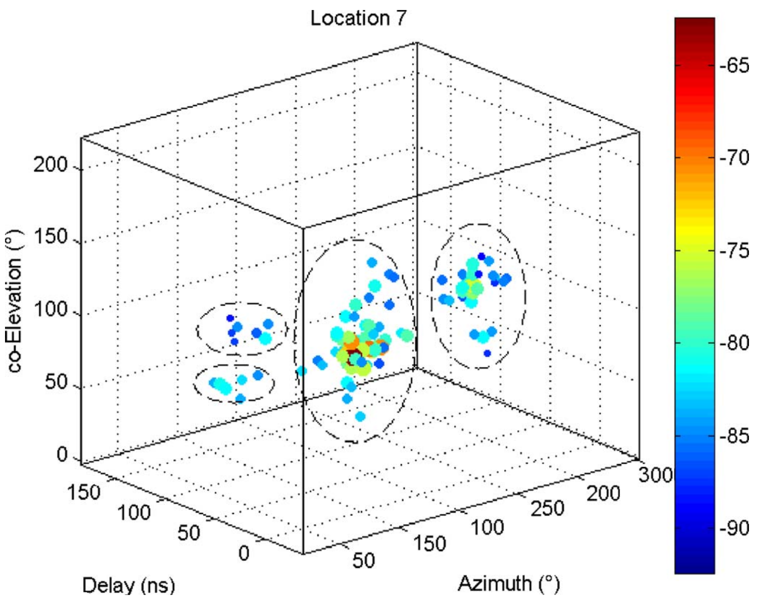
- DOA depends on DOD => double-directional
- DOAs and DODs different for different delays
- Strong discrete multipath components, which appear in
- Clusters…
- plus diffuse power
- As a consequence, MIMO exhibits
  - extremely high local variation
  - time dependence
  - frequency-selectivity



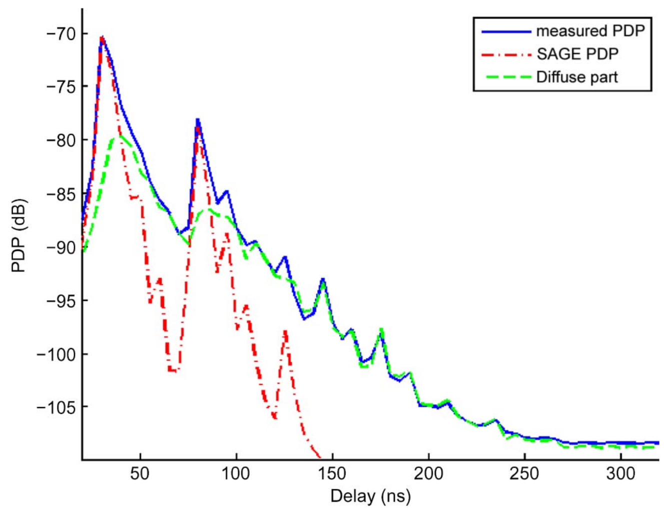
Diffuse Multipath Component DMC

A. Richter, PhD thesis, TU Ilmenau, 2005

- Discrete multipath does not fully account for power delay profile
- “diffuse” remainder due to multiple small scattering contributions
- not noise!

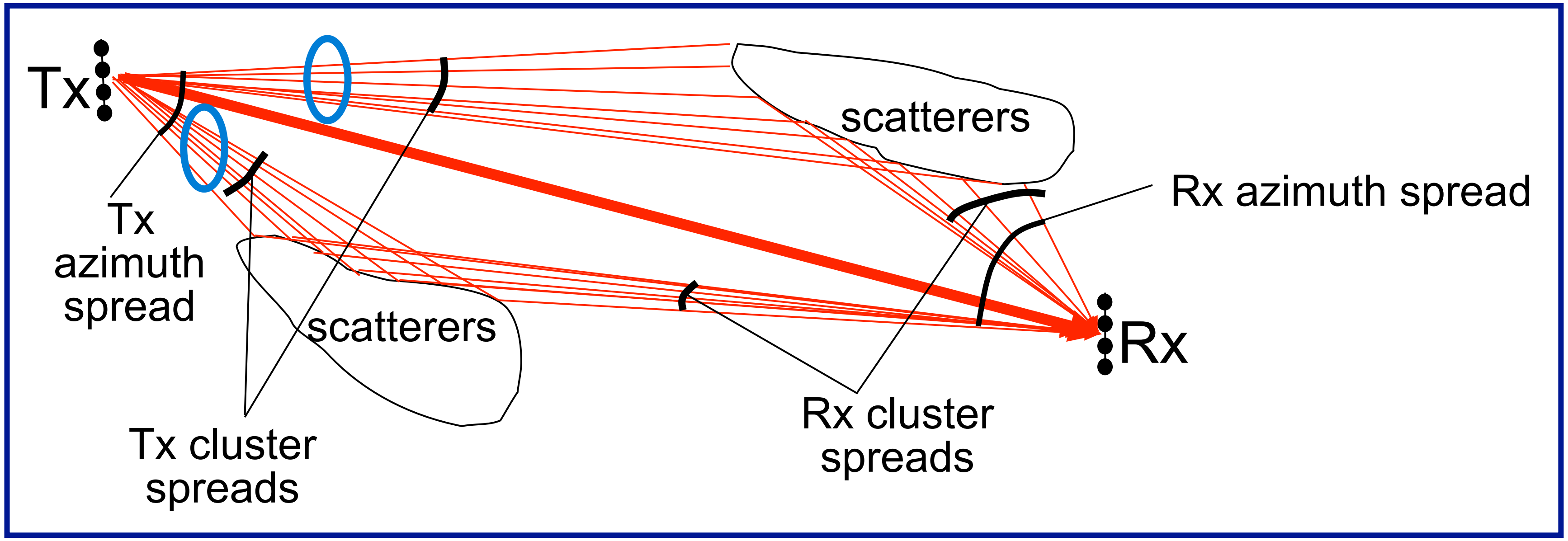


Quitin et al, IEEE VT 2010



Multipath Clusters

- **Clusters** modify the temporal and angular dispersion:



- Global dispersion parameters:
  - rms delay spread
  - (total) rms angular spreads (*"composite AS"*)

- Cluster dispersion parameters:
  - cluster rms delay spread
  - cluster rms angular spreads (*"intra-cluster AS", "component AS"*)

Outline

Modeling Philosophies

MIMO Measurements

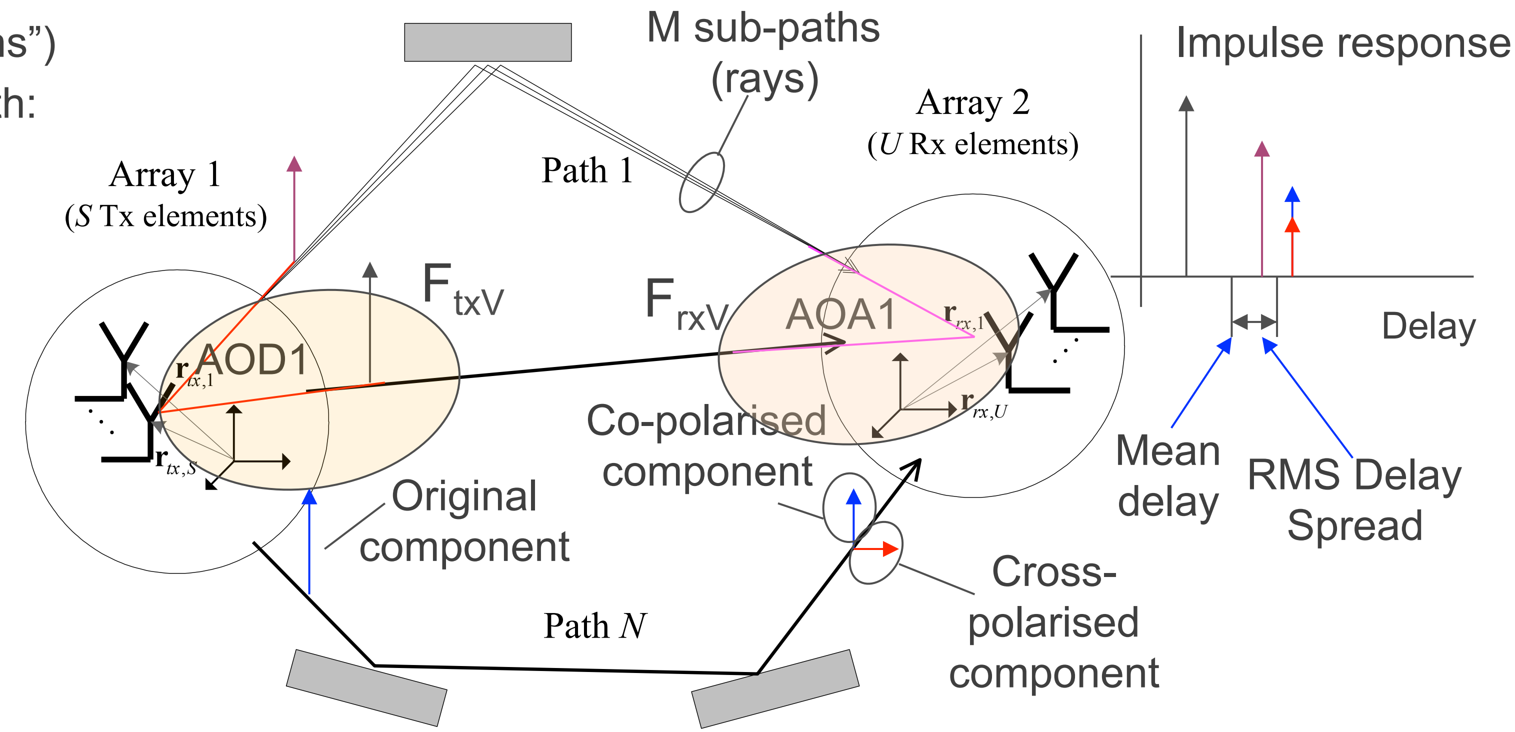
Two Models

- WINNER II
- why-sell-burgers?

WINNER II: MIMO link with details

N clusters ("paths") each defined with:

- Delay
- AoD
- AoA
- Gain
- Cross-pol. (XPR).
- Sub-paths ("MPCs", "rays")



WINNER Channel Model for 4G evaluations

- A Geometry-based Stochastic Channel Model
  - as 3GPP SCM, COST 273, etc. models.
- Based on extensive measurements in WINNER (+ literature).
  - Parameters for more than 10 propagation environments
  - Two levels of randomness
  - for system-level modelling
- Carrier frequency range 2 – 6 GHz
- Bandwidth 100 MHz
- Drop-based time evolution

- Selected by ITU-R for IMT-Advanced validation (4G)
- COST 2100 => MIMO Multilink Model

Model MIMO matrix directly (Plan B)

Advantageous for system simulations

- when Rx and Tx arrays already have been specified (N,M, d, polarization,…)
- when we need to produce a set of MIMO matrices

We treat ***H*** as a random variable

- completely random? No, correlation comes into play

- Correlation of sub-channels as a consequence of both
  - the antenna arrays and
  - the propagation environment
- In MIMO it is always a correlation between sub-channels, not antenna signals!

Full CSI, partial CSI, no CSI?

- no CSI: full correlation matrix $\boldsymbol{R}_{\mathrm{H}}$ matters

$M{\cdot}N \times M{\cdot}N$

Modeling the correlation matrix R_H

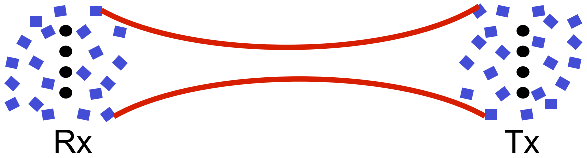
1. No correlation between any two elements of $\boldsymbol{H}$

$\boldsymbol{R}_H = \boldsymbol{I}_{\mathrm{MN}}$ $\quad\quad$ $\boldsymbol{H} = \boldsymbol{H}_u$ (i.i.d., "rich scattering")

2. receive correlation $\quad\quad$ transmit correlation

$$\mathbf{R}_{\mathrm{R}} = E\left[\mathbf{H}^{*}\mathbf{H}^{\mathrm{T}}\right] \quad\quad \mathbf{R}_{\mathrm{T}} = E\left[\mathbf{H}^{\mathrm{H}}\mathbf{H}\right]$$

3. *Separately* correlated "Kronecker model" $\quad \boldsymbol{R}_H = \boldsymbol{R}_{\mathrm{R}} \otimes \boldsymbol{R}_{\mathrm{T}}$



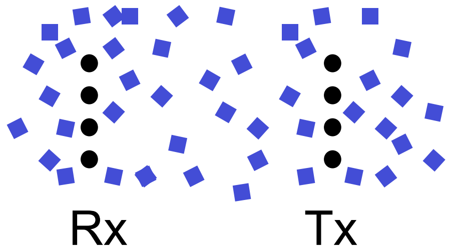
$$\boldsymbol{H} = \boldsymbol{R}_{\mathrm{R}}^{1/2}\,\boldsymbol{H}_u \boldsymbol{R}_{\mathrm{T}}^{1/2}$$

Any **transmit antenna weight results** ***in one and the same*** **receive correlation!**

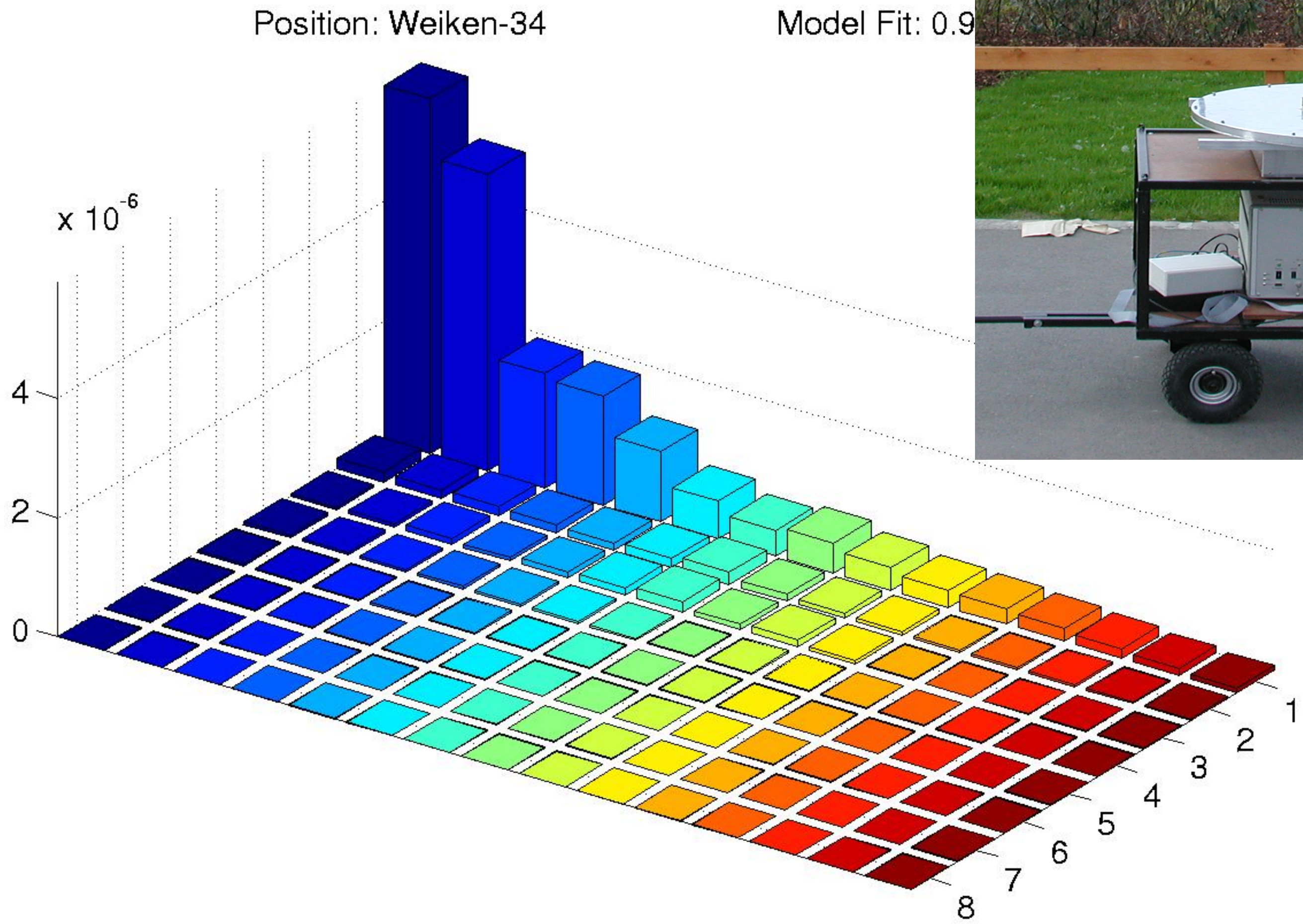
[why]-[sell]-[burger] model

Weichselberger et al.,
IEEE Trans Wireless Comm, 2006

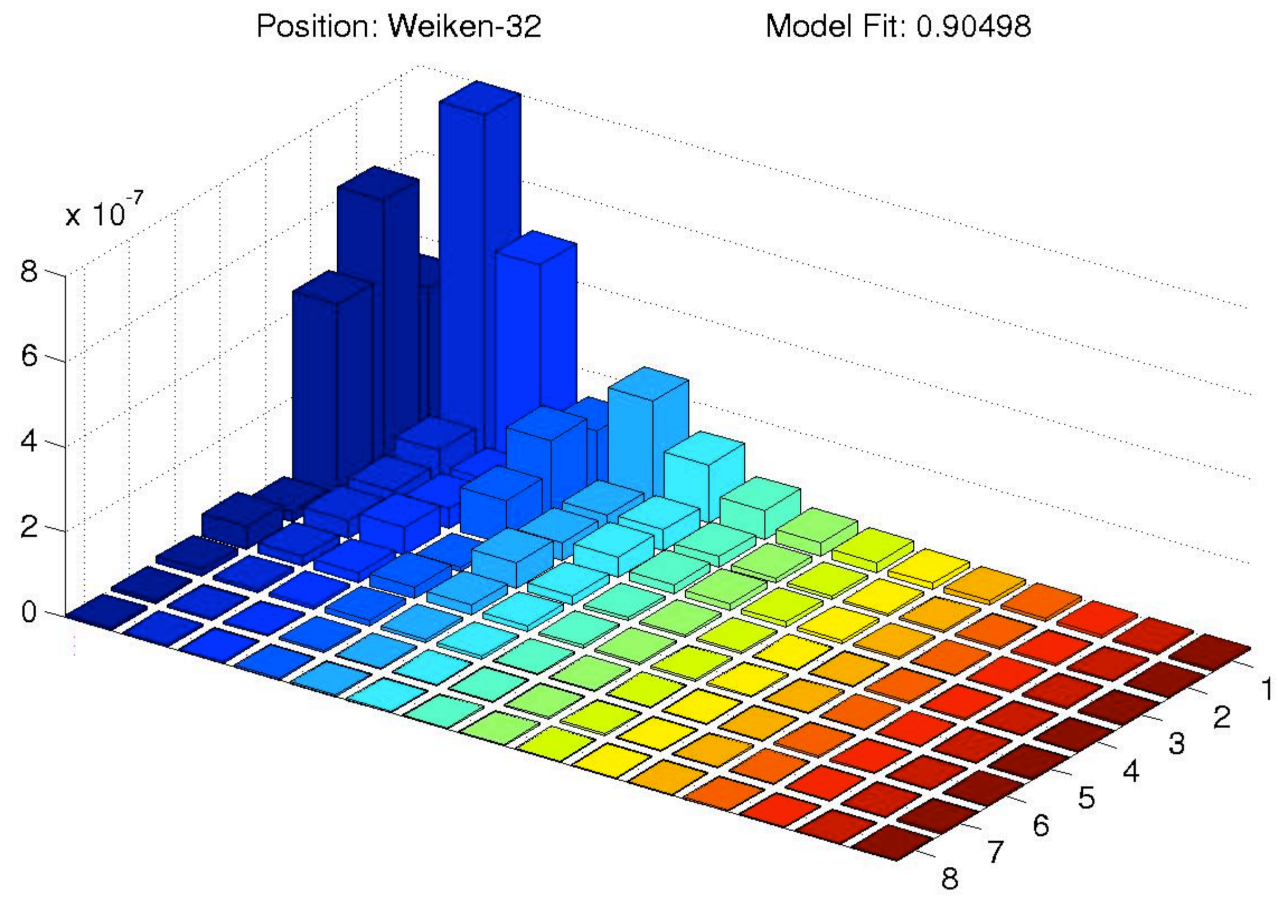
- The [why]-[x]-[sell]-[burger] model is based on MIMO eigenmodes
- models the channel by a coupling matrix Ω of transmit and receive eigenmodes
- accounts for joint correlation of Tx and Rx sides
- reveals which MIMO scheme is best in a given environment
- has been proven independently to render mutual information („capacity“), diversity order,... better than any other model so far
- in any environment (in-, outdoor, LOS)
- at any frequency 0.3 through 5.8 GHz



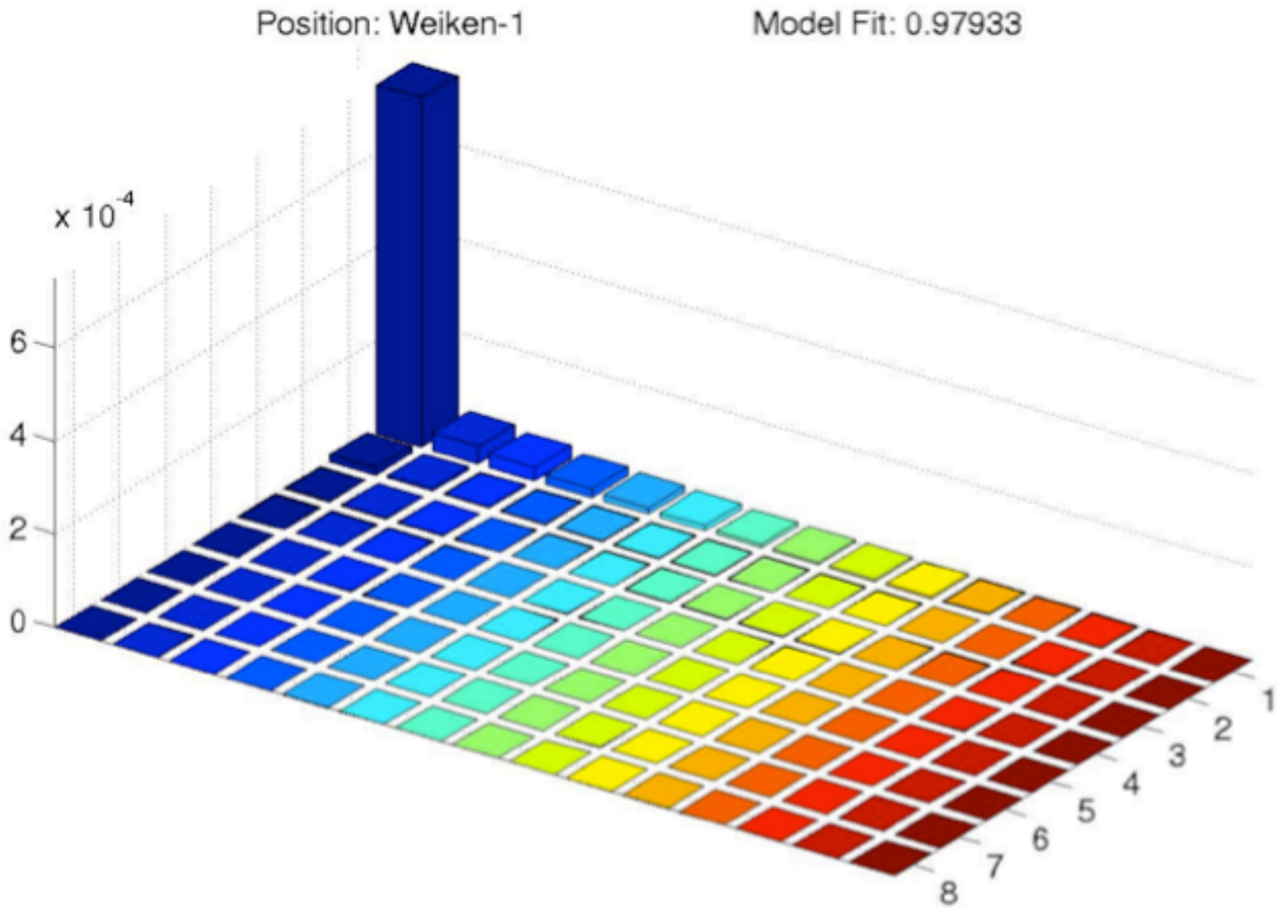
Weikendorf 34, TX diversity, RX beamforming



Weikendorf 32, multiplexing up to 5 streams



Weikendorf 1, beamforming at RX and TX

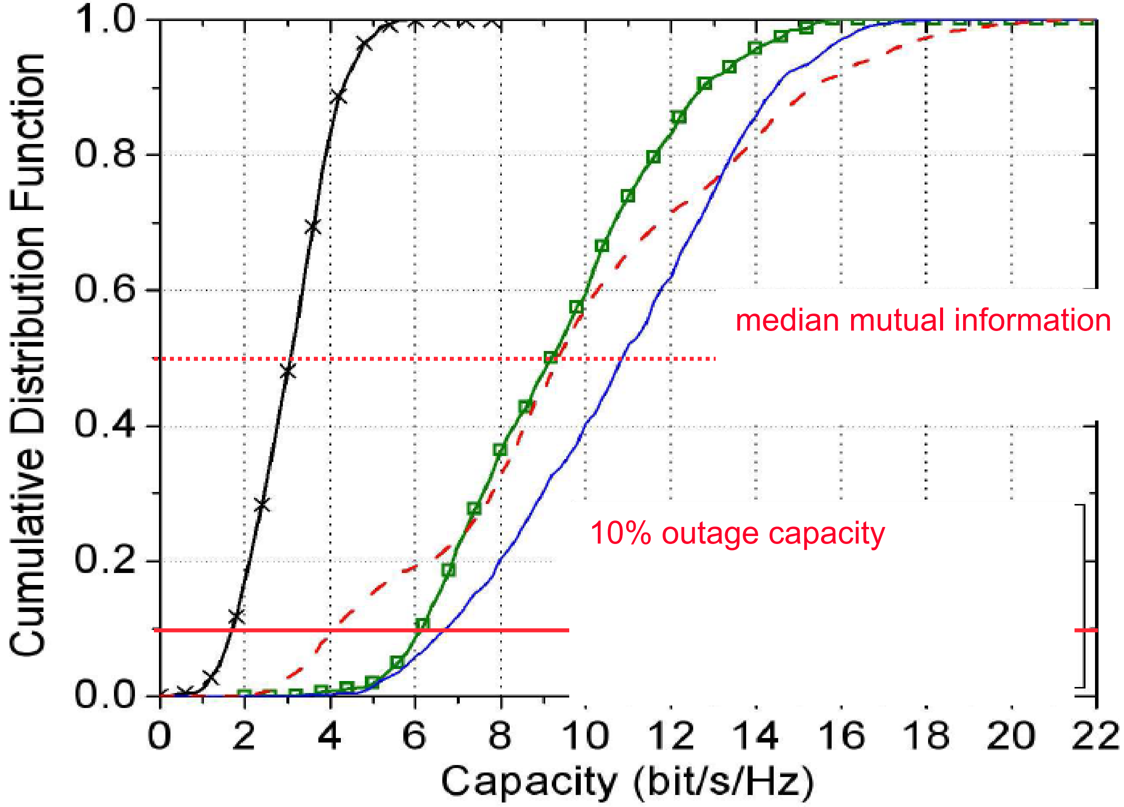


What is a good MIMO channel model?

Let's look on some metrics

- Mutual information
  - Eigenvalues λ_i of $\boldsymbol{HH}^H$
  - Distribution of λ_i
  - Condition number CN
  - Outage capacity
- Diversity order (Ivrlac &

- Which effect?
- How many parameters?



$\sum_{i=1} \lambda_i^2$

A myth: „Capacity is a sufficient metric for deciding whether a MIMO model is good or not"

- All MIMO models I have seen render ergodic capacity within + - 20% correctly
- So what does *agreement* of modelled and measured capacities tell us?
- Not very much!

Ergodic MIMO capacity is a **necessary** but neither a **sufficient** nor a **sensitive** metric.

Open challenges

- Diffuse multipath
- Vehicle-to-vehicle
- Body-area networks
- Over-the-air (OTA) MIMO terminal testing

"Didn't we have already enough channel research?"

No, we have been interested in the
average channel,
but in the future we will have to be interested in the
MIMO channel *here and now*.

Link to collection of NEWCOM++
MIMO measurements
https://portal.ftw.at/workspaces/channeldb/measurements

Thank you!