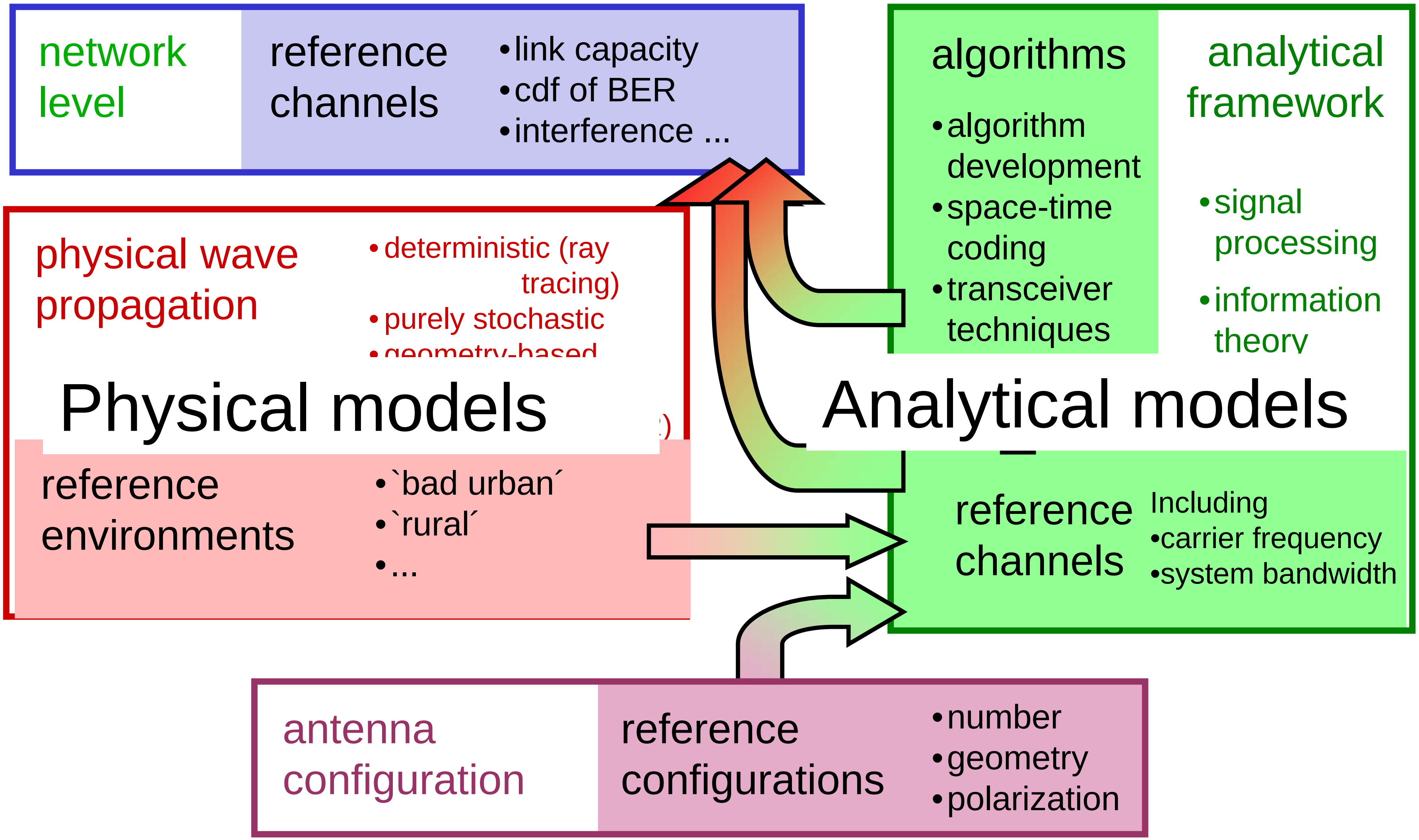
On MIMO Channel Models for LTE

Ernst Bonek
Institut für Nachrichtentechnik und Hochfrequenztechnik
Technische Universität Wien
and
Forschungszentrum Telekommunikation Wien

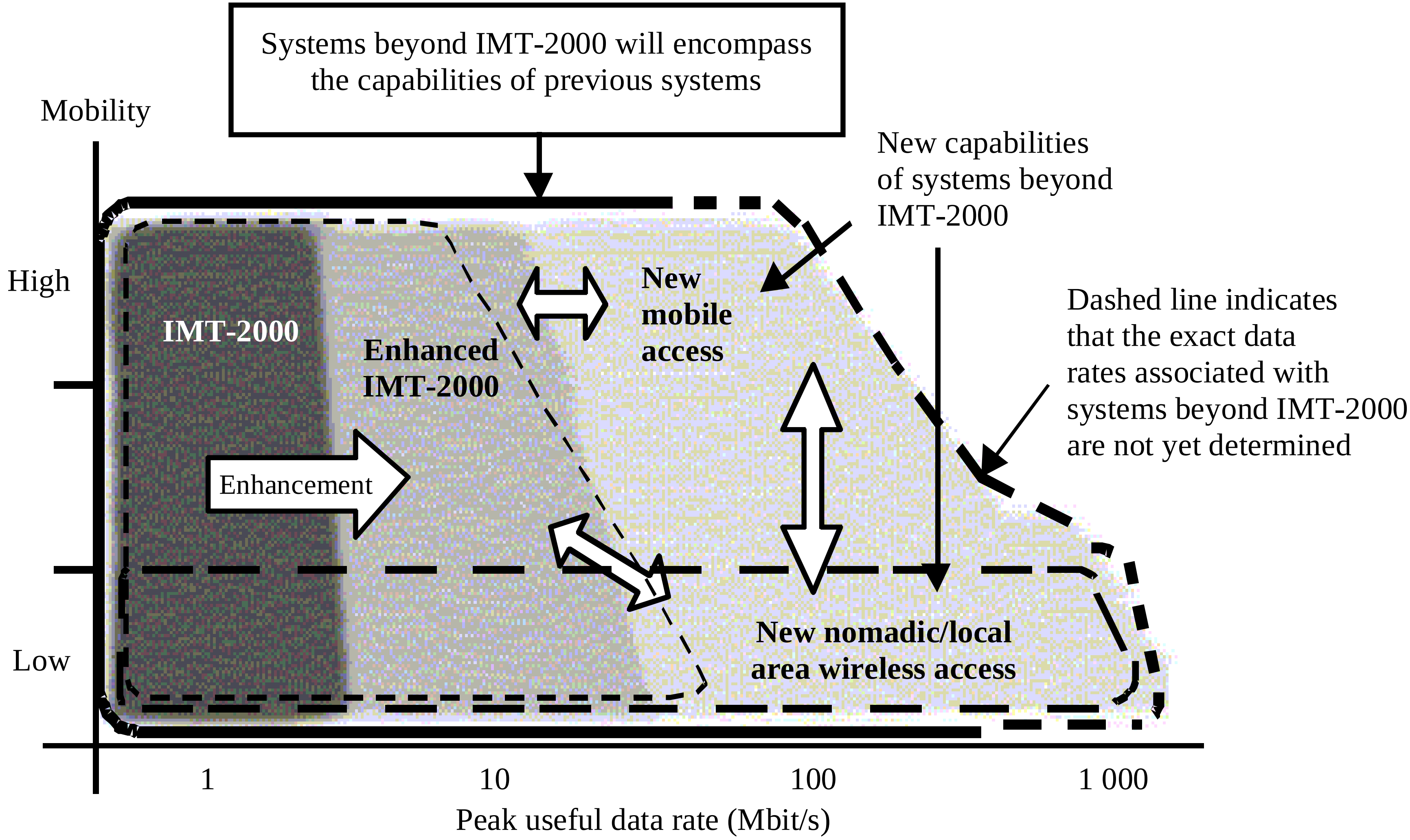
Turku

16 January 2009

MIMO channel models – an overview



International Telecommunications Union ITU-R: 1 Gbit/s



Eventually…

- Eventually, 3gpp has decided to use MIMO
- Physical Downlink Shared Channel (PDSCH)
- Up to 300 Mbit/s per cell or sector
- 2x2, 4x2, and 4x4 antennas
- TX Diversity (open loop) and Spatial Multiplexing (closed loop)
- S(ingle)U(ser)-MIMO
- M(ulti)U(ser)-MIMO (”Virtual” MIMO)

- Instead of full CSI feedback, stored ***H***-matrices are used (“Preferred Matrix Index”) – How to obtain these matrices?
- “conformance tests for time variable channels not considered at the moment” – By which channel models?

Outline

- What kind of MIMO models?

- The WINNER II Channel Model(s)
  - Clusters
  - Double-directional

- The Random-Cluster Model
  - Clustering framework
  - Parameterization
  - Results

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

- Conclusions

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WINNER II channel model(s)

- A *stochastic geometry-based* radio channel model, similar to 3GPP SCM and COST 273
- *Double-directional* ☺
- Separates antennas from propagation environment ☺
- *Cluster-based* ☺
  - Clusters are placed to generate given azimuth power spectra at Tx and at Rx (“Wrapped Gaussian”)
- each cluster has 20 multipath components ☹
- **18 different scenarios** parameterized ☺
  by a large number of measurements ☺
  - Outdoor, indoor, outdoor2indoor; with and without LOS, high speed
- WINNER model is very general and covers many scenarios ☺
- Number of taps depend on the scenario, BUT
  each tap is again modeled as one single cluster ☹
- Focuses on **global** channel properties rather than on **cluster** properties
- Describes channel variability well ☺
- Smothly time-varying channels? ☹
- Selected by ITU-R for IMT-Advanced candidate testing

Types of propagation models ("physical" models)

- Deterministic
  - Ray-tracing or ray-launching
  - Stored channel

Merits

good agreement with physically existing results (site-specific)
reproducible

Problems

selected environments need not be representative
large data bases required
expensive to produce
parameters cannot be changed easily

Types of propagation models ("physical" models)

- Purely stochastic

Multidimensional probability density function of channel impulse response

Merits:

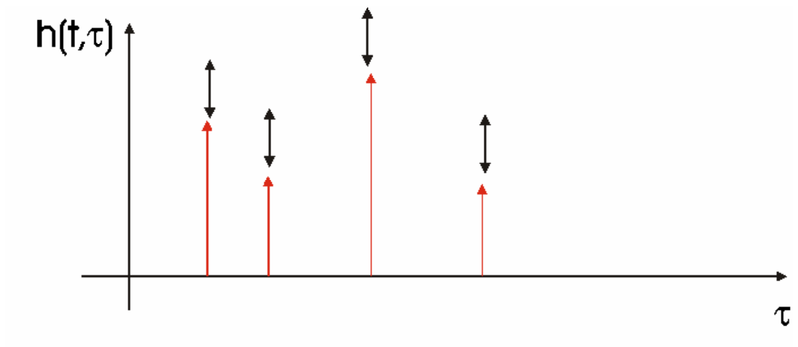
fast

Problems:

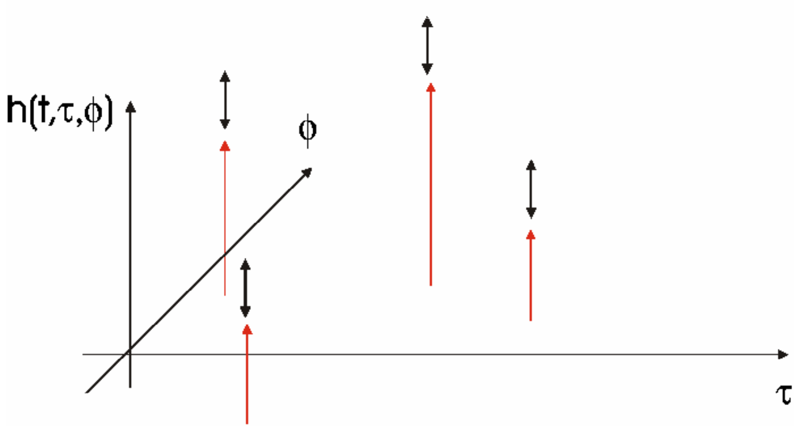
difficult to parameterize over large areas

questionable concepts like rms angular spread

Standard WSSUS model – tapped delay line realization



Generalization to spatial dimension



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Geometry-based Stochastic Channel Model (GSCM)

- Prescribe probability density function of *scatterers*
- Groups of scatterers, fixed in space, produce clusters
  - Increase of temporal and angular dispersion

Merits

Better for large areas

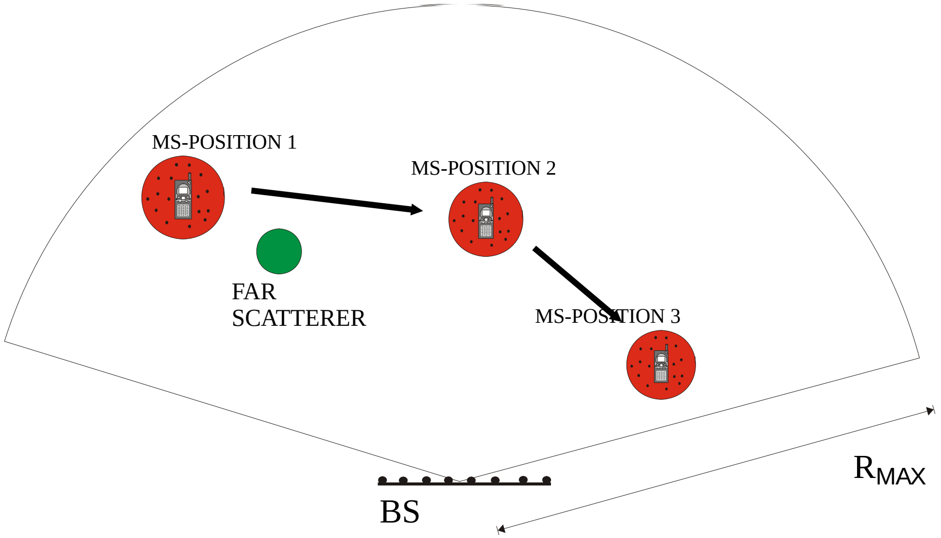
…and

Temporal evolution

Interference

Spatial correlation

between interfering mobiles



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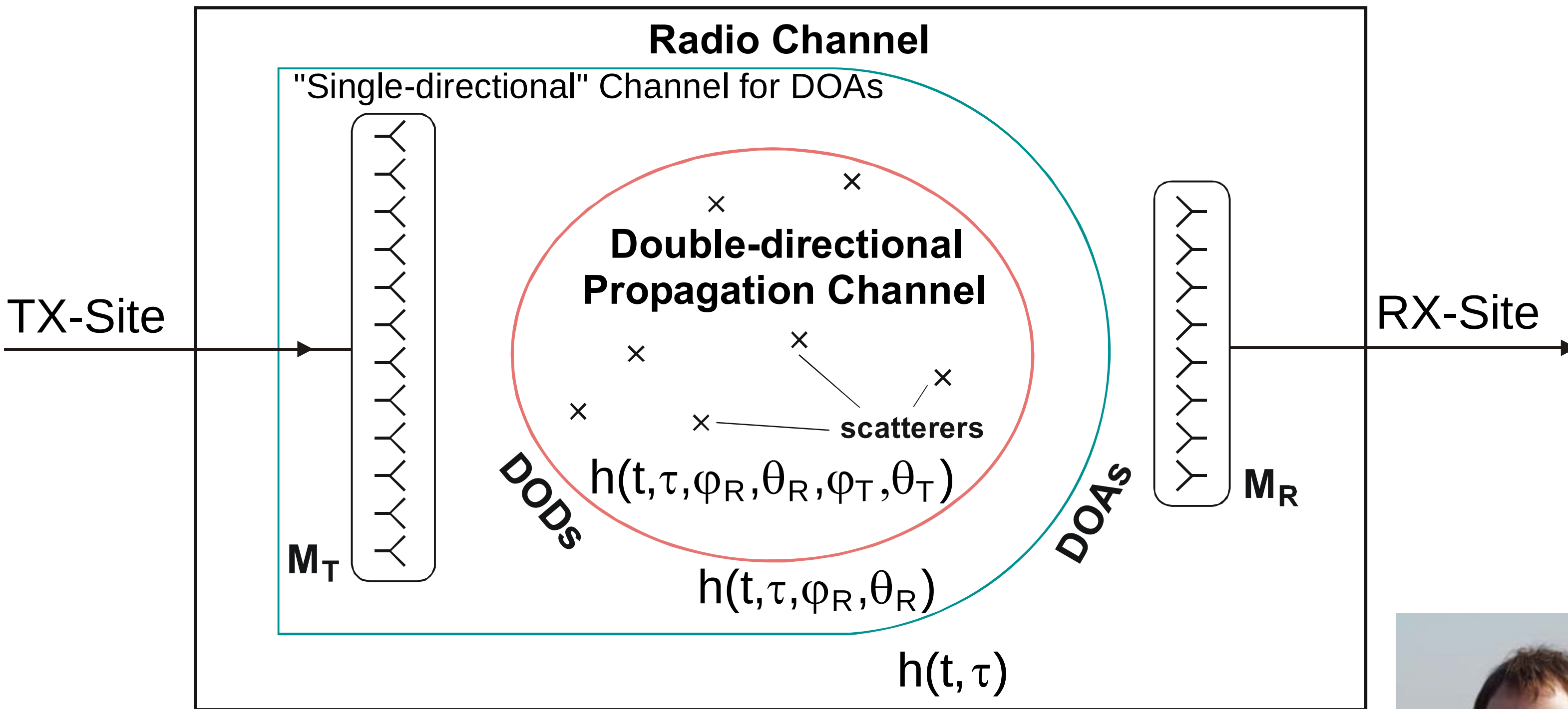
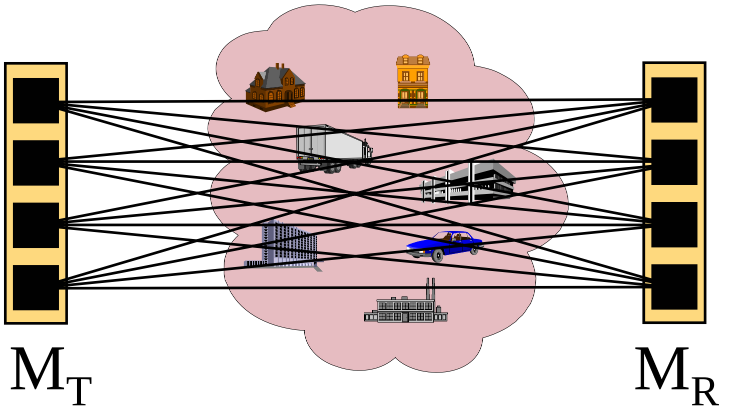
The Double-directional Propagation Channel



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

The Double-directional MIMO Channel

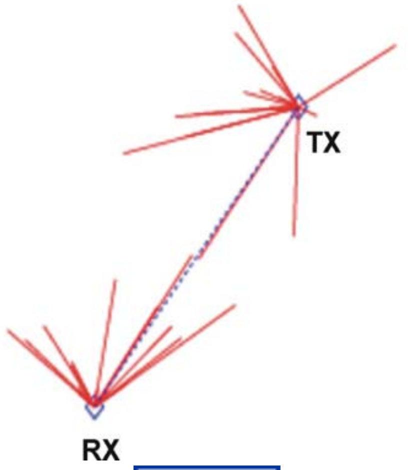


- We can identify individual multipath components in a given environment
- We can trace each multipath components from TX to RX

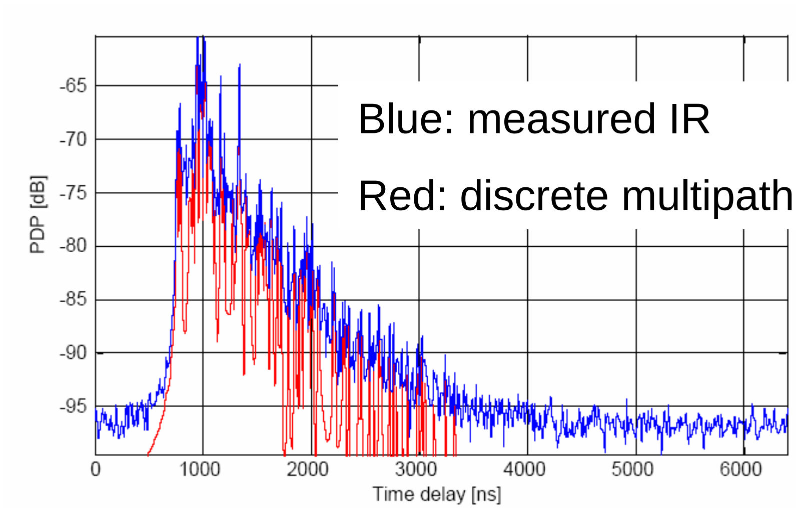
Propagation directions at ***both*** link ends

DoA and DoD

=> double-directional viewpoint

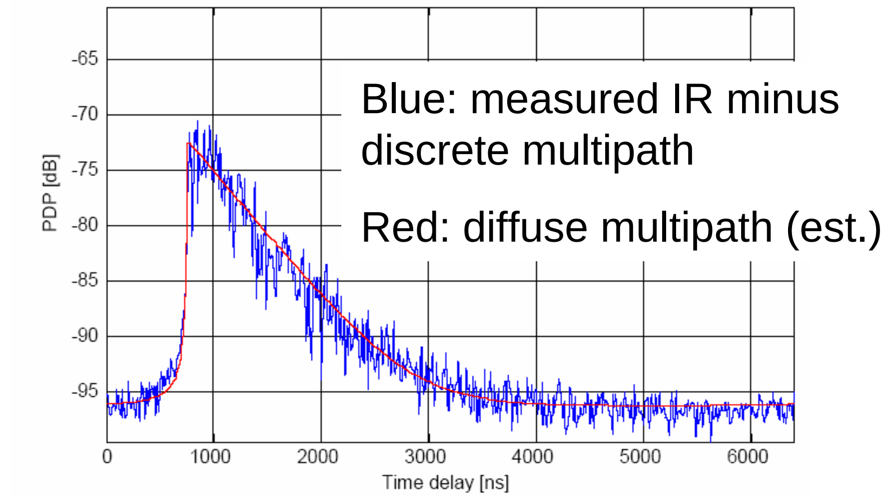


Diffuse Multipath Component (A. Richter, TU Ilmenau)



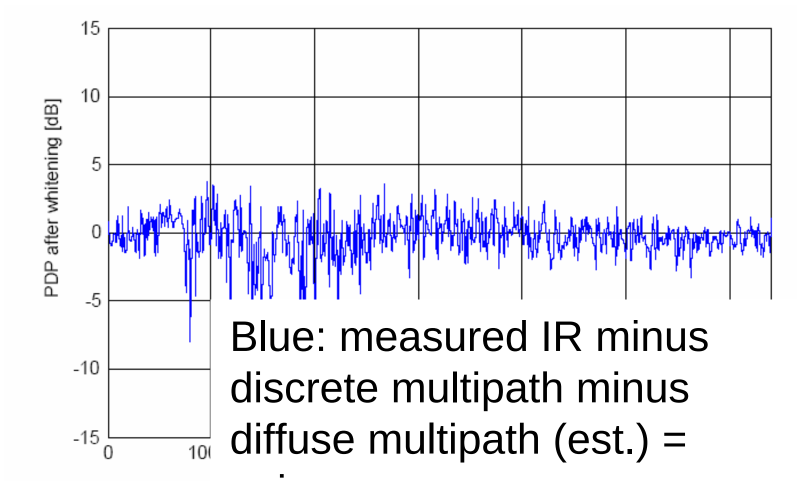
Blue: measured IR

Red: discrete multipath

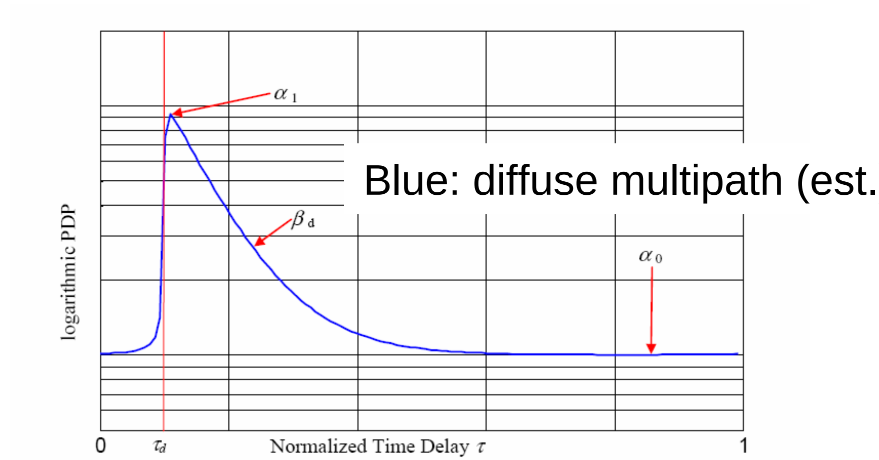


Blue: measured IR minus discrete multipath

Red: diffuse multipath (est.)



Blue: measured IR minus discrete multipath minus diffuse multipath (est.) = noise



Blue: diffuse multipath (est.)

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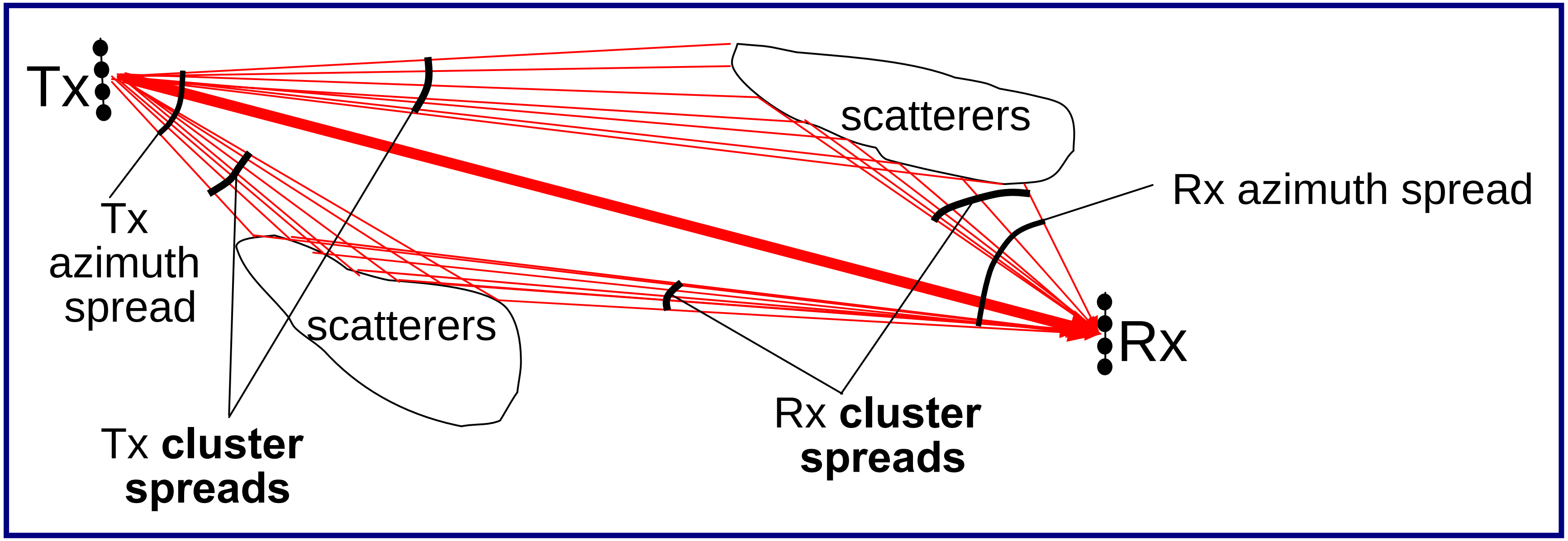
Why clusters?

- Practically all measurements show them[1]
- Clusters reduce the number of parameters considerably
- Many “standard“ MIMO channel models rely on clusters:
  - 3GPP-SCM
  - IEEE 802.11n
  - COST 273
  - WINNER II

[1] Xiao,Burr, Hentilä, Kyösti, EuCAP 2007

Multipath Clusters

- **Clusters** lead to temporal and angular dispersion:

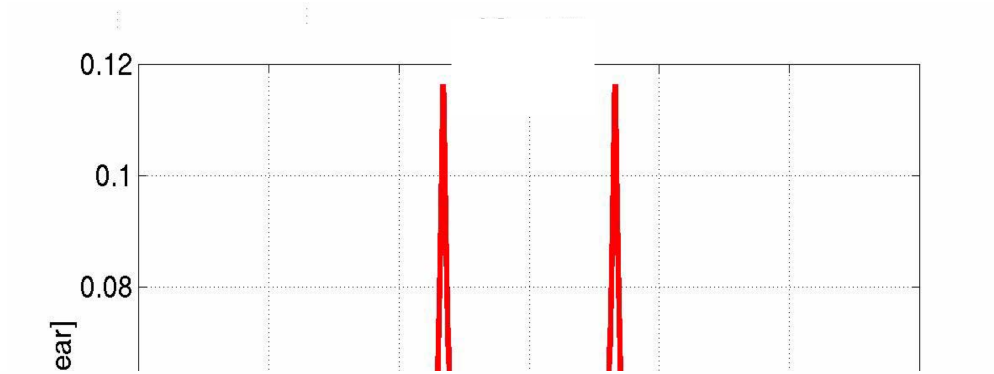


- Global dispersion parameters:
  - rms delay spread
  - rms angular spreads

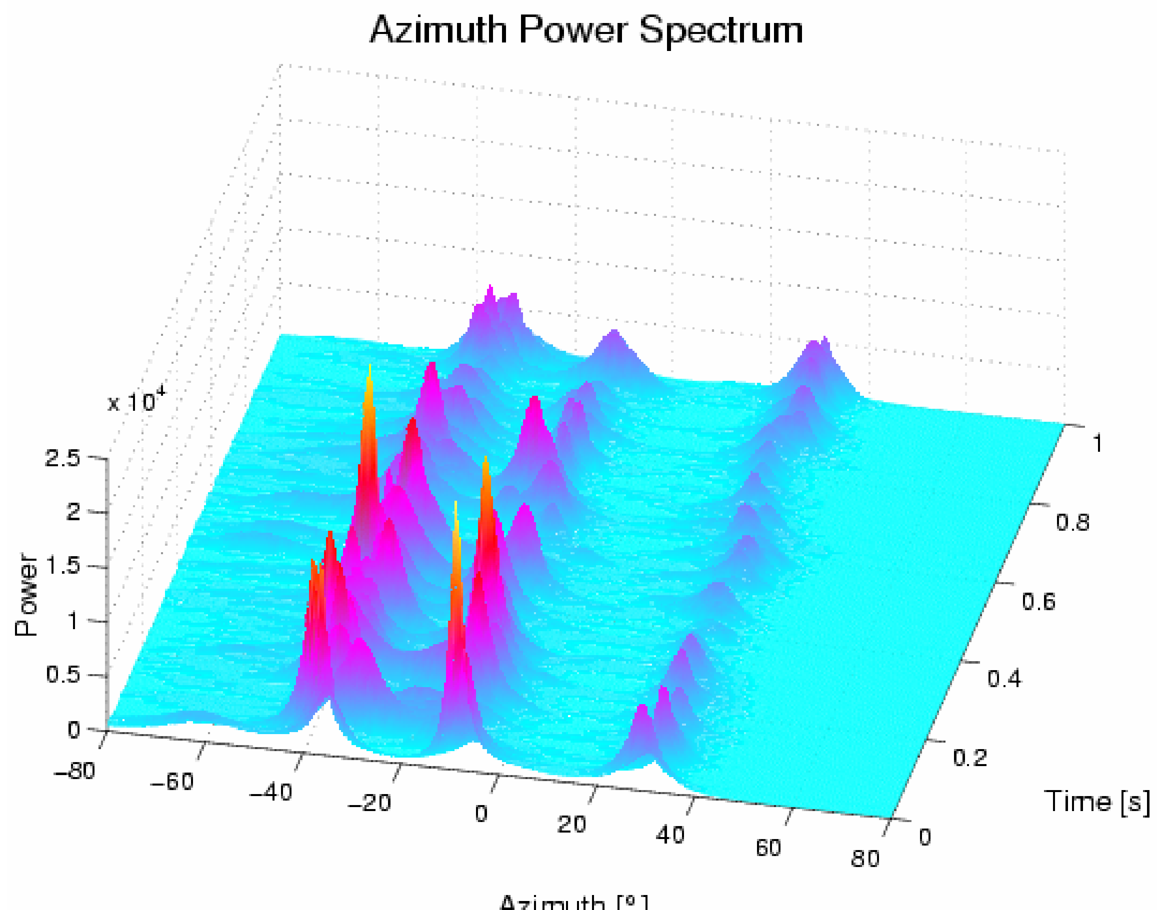
- Cluster dispersion parameters:
  - cluster rms delay spread
  - cluster rms angular spread

RMS Global Angular Spread ?

- $$\mathrm{rmsAS} = \frac{\sqrt{\int_{-180^\circ}^{180^\circ} (\varphi - \overline{\varphi})^2 \, \mathrm{APS}(\varphi) d\varphi}}{\sqrt{\int_{-180^\circ}^{180^\circ} \mathrm{APS}(\varphi) d\varphi}}$$



- rmsAS:= 20° = 20°!
- Much better: angular spread for each cluster



„component“ angular spread

PhD thesis Kuchar 1999
Kuchar, A. et al., IEEE Trans. Veh.Techn. 51, 2002, p.1279 ff

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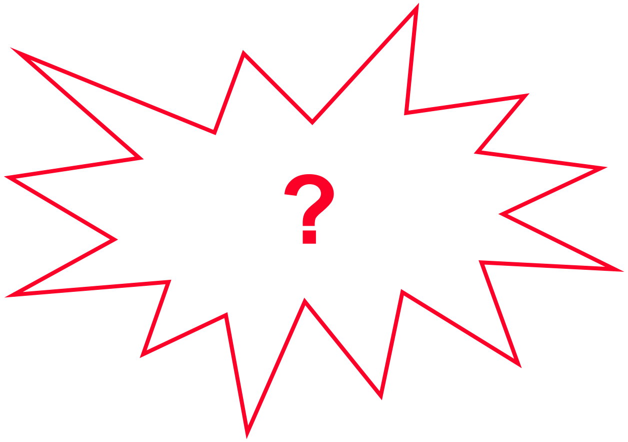
The Random-Cluster Model

N. Czink, PhD thesis, 2007



- Prescribes all environmental parameters by a single multi-dimensional pdf
- containing the distributions of the cluster parameters
- Parameterized directly from measurements
- Automatic clustering without user intervention
  - speedy
  - objective

Environment parameter pdf

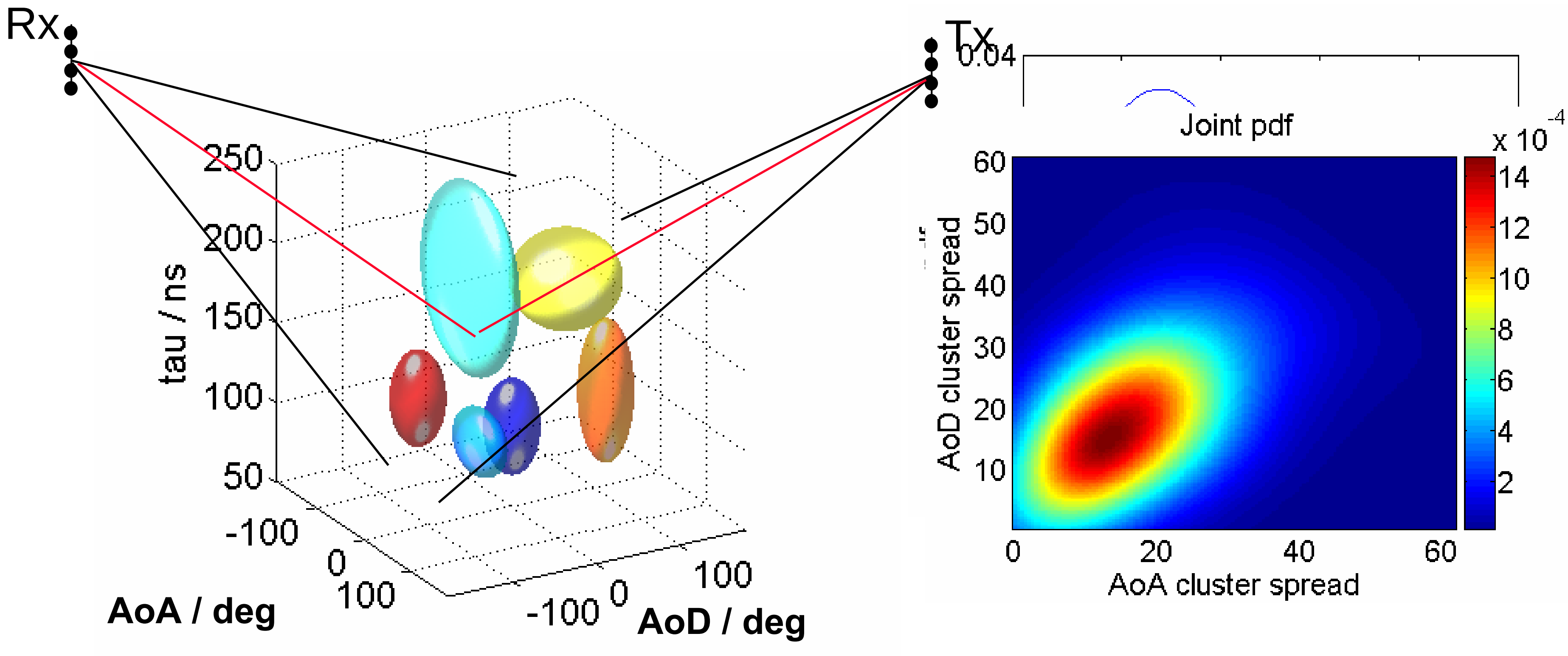
- The environment parameter pdf is the
  - **multivariate distribution** of the
  - **cluster parameters** Θ_c

$$p_{\Theta_c}(\boldsymbol{\theta}_c)$$

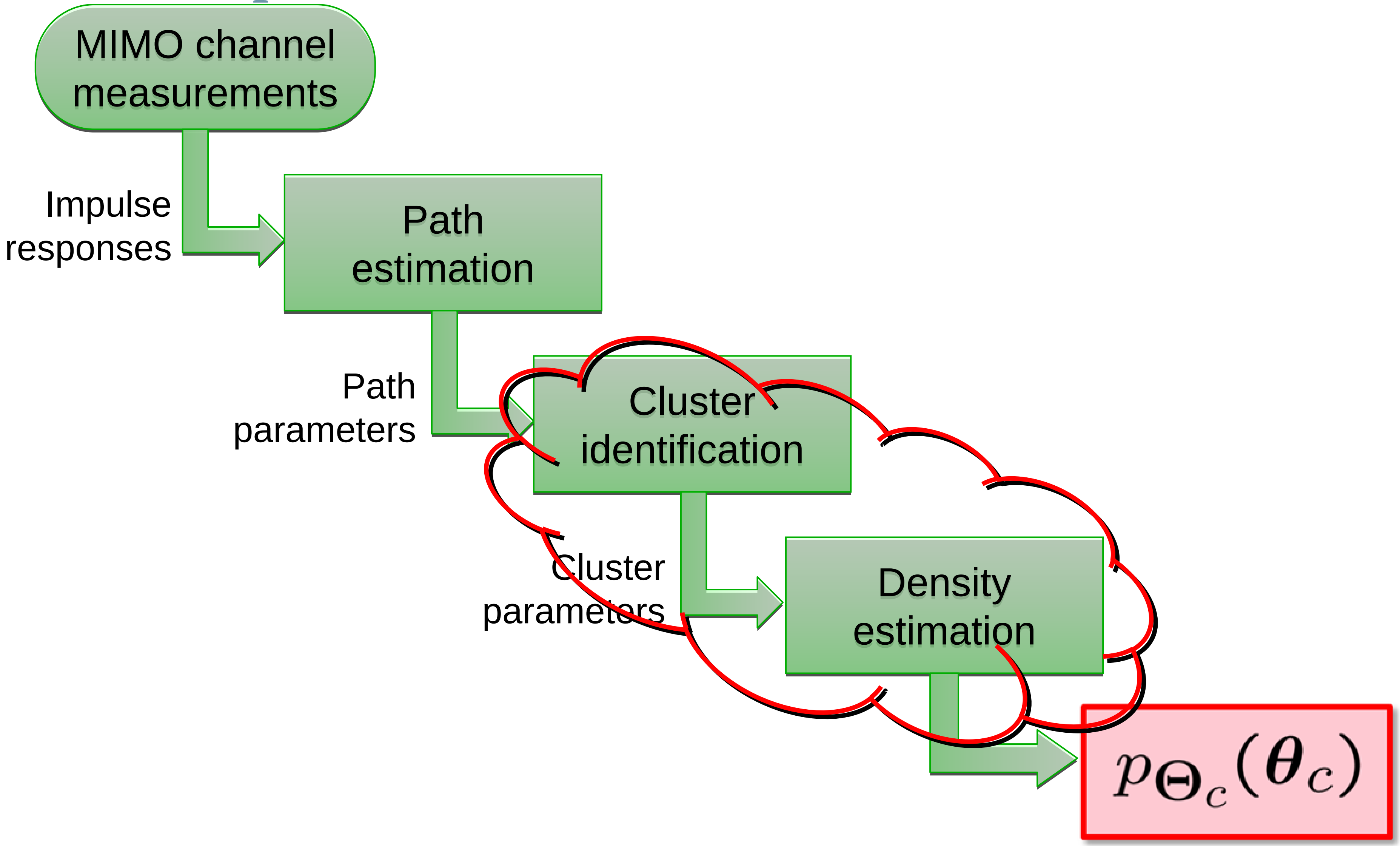
- Cluster parameters
  - **position parameters**: mean delay, DoA, DoD
  - **power parameters:** cluster power, snapshot power
  - **size parameters**: rms delay spread, DoA spread, DoD spread
  - **number parameters**: number of paths, clusters
  - **movement parameters**: **change rates** of cluster power, mean delay, DoA, DoD
  - **lifetime parameter**: cluster lifetime

Cluster characteristics

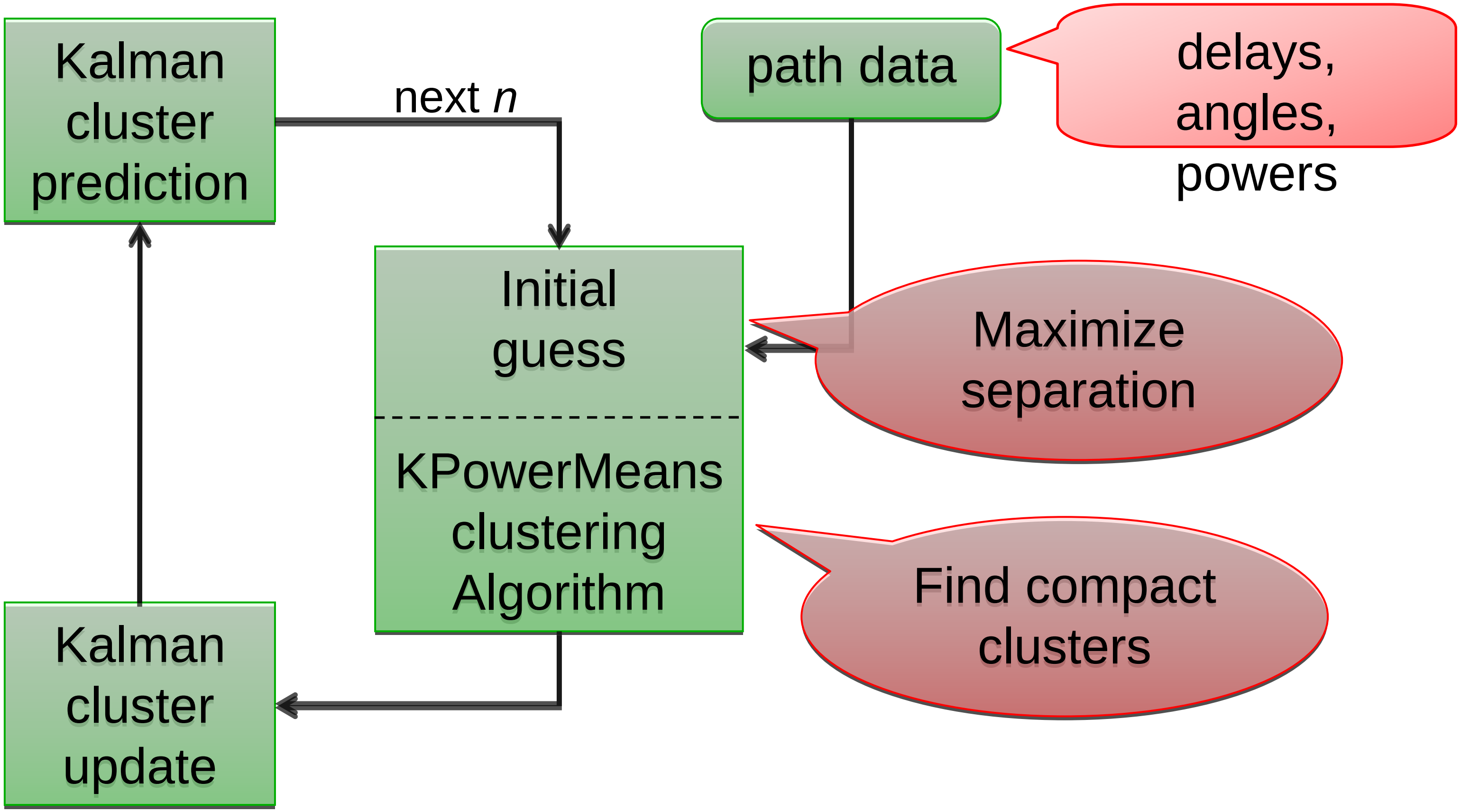
- A cluster consists of a number of multi-path components, where the parameters of all paths within a cluster share the *same* distribution
- Each snapshot of a environment ("scenario") consists of multiple clusters
- The parameter distributions are *inter*dependent.



RCM parameterization



Clustering-and-tracking framework



Number of clusters?

Czink et al, IST Summit 2006

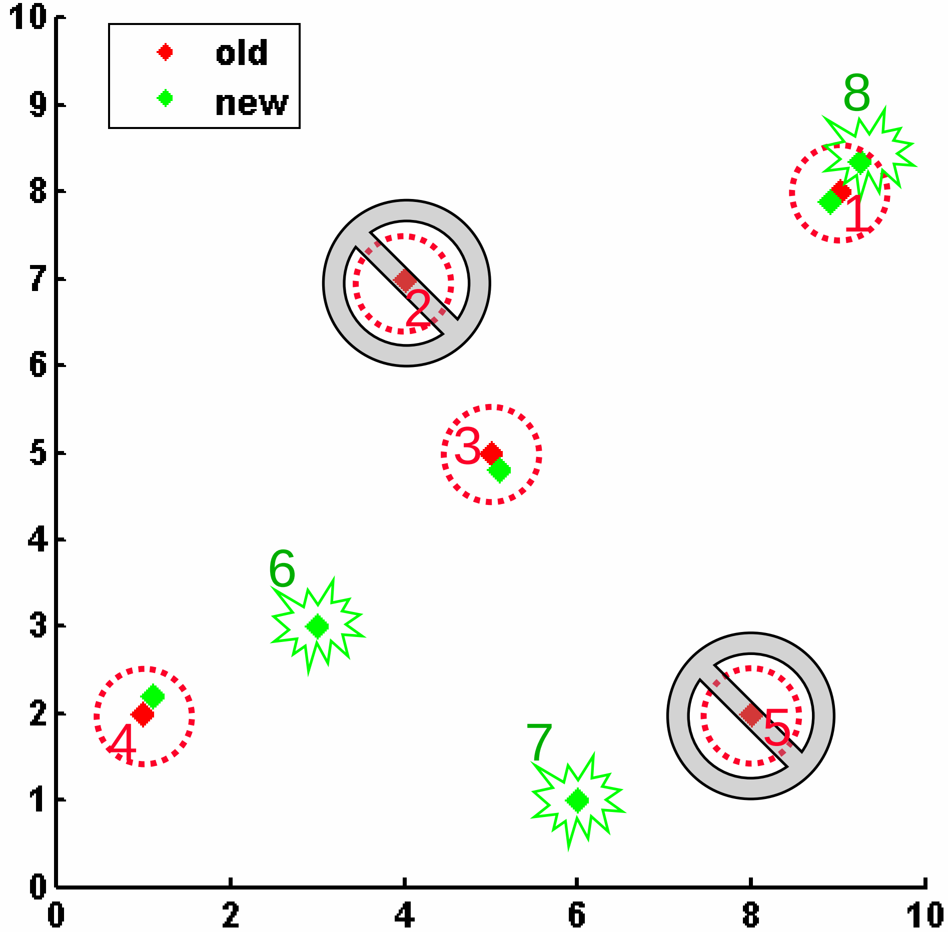
For $N_c = N_{c\ min}$ To $N_{c\ max}$ number of clusters:

- Estimate cluster parameters for N_c clusters
- Recreate environment using the model using N_c clusters
- Compare modeled environment to measured environment
- If the modeled environment is “close enough” to reality, stop.
  Optimum number of clusters = N_c
- Else Next N_c

Advantage

- The number of clusters is mathematically defined by a tradeoff between model complexity and modeling error

Cluster Tracking Algorithm



Algorithm:

1. Old clusters have unique cluster-ID
2. Old clusters have tracking range
3. Find "outliers" → New cluster
4. Closest new centroid in tracking range → Tracked cluster
5. Other new centroids → New cluster
6. Old clusters that weren't tracked have died

… tracking range

Measurement equipment

Elektrobit PropSound CS™ Channel Sounder

Parameter	2.55 GHz	5.25 GHz
Transmit power [dBm]	26	26
Chip frequency [MHz]	100	100
Channel sampling rate [Hz]	92.6	59.4
Measurable excess delay [μs]	2.55	2.55

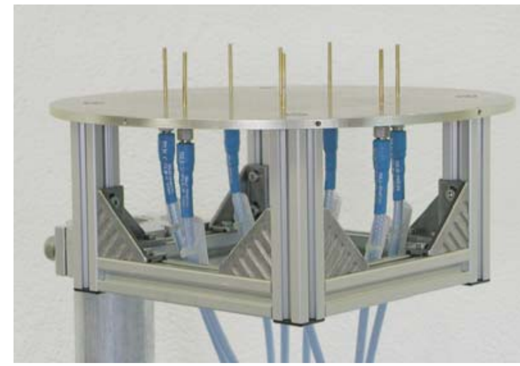
Antennas

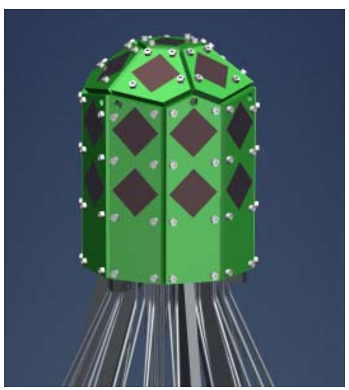
- Omni-directional antennas at both link ends to capture the full spatial domain

Tx

H(t,τ) @ 2.55 GHz: 56 × 8

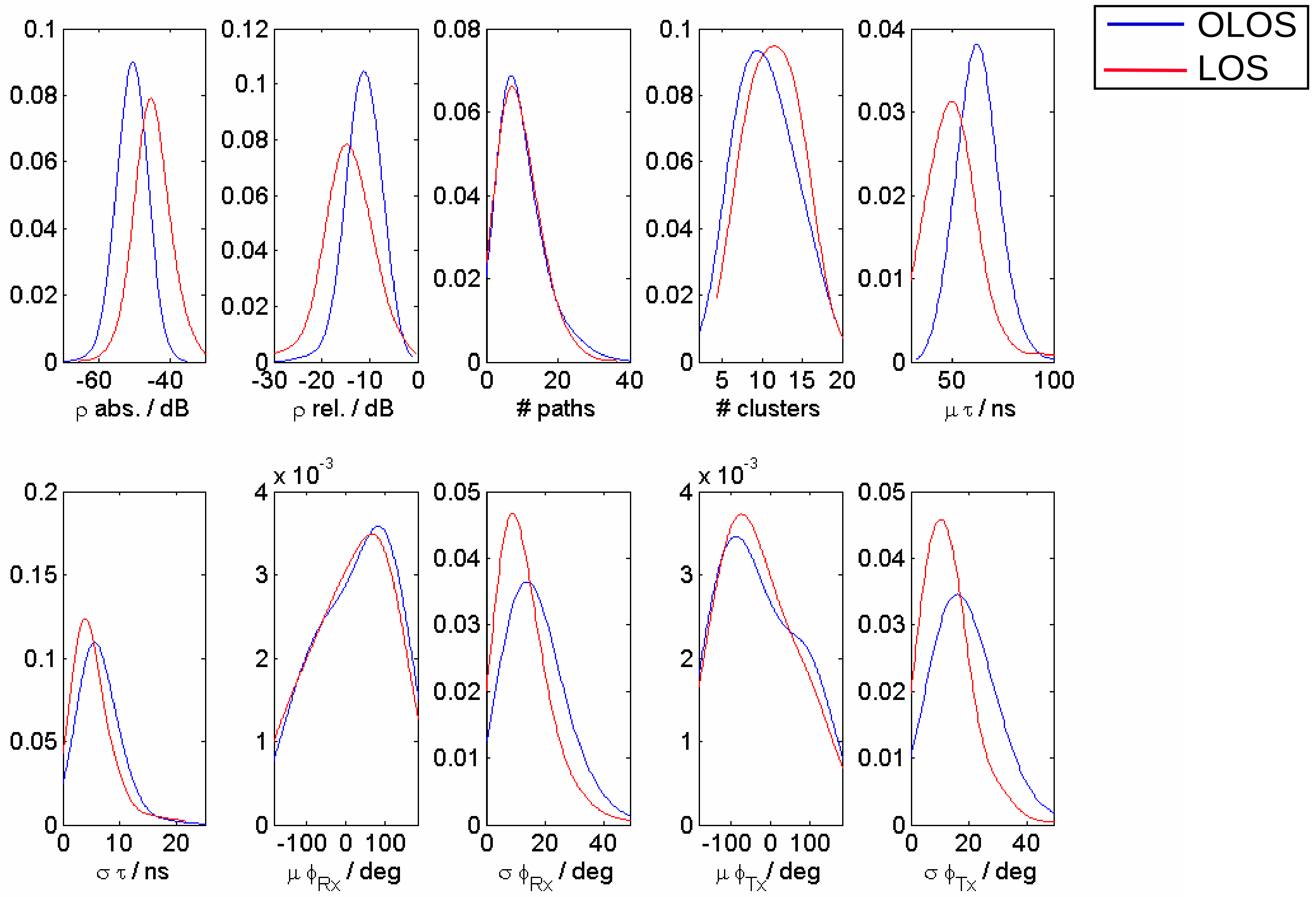
Rx



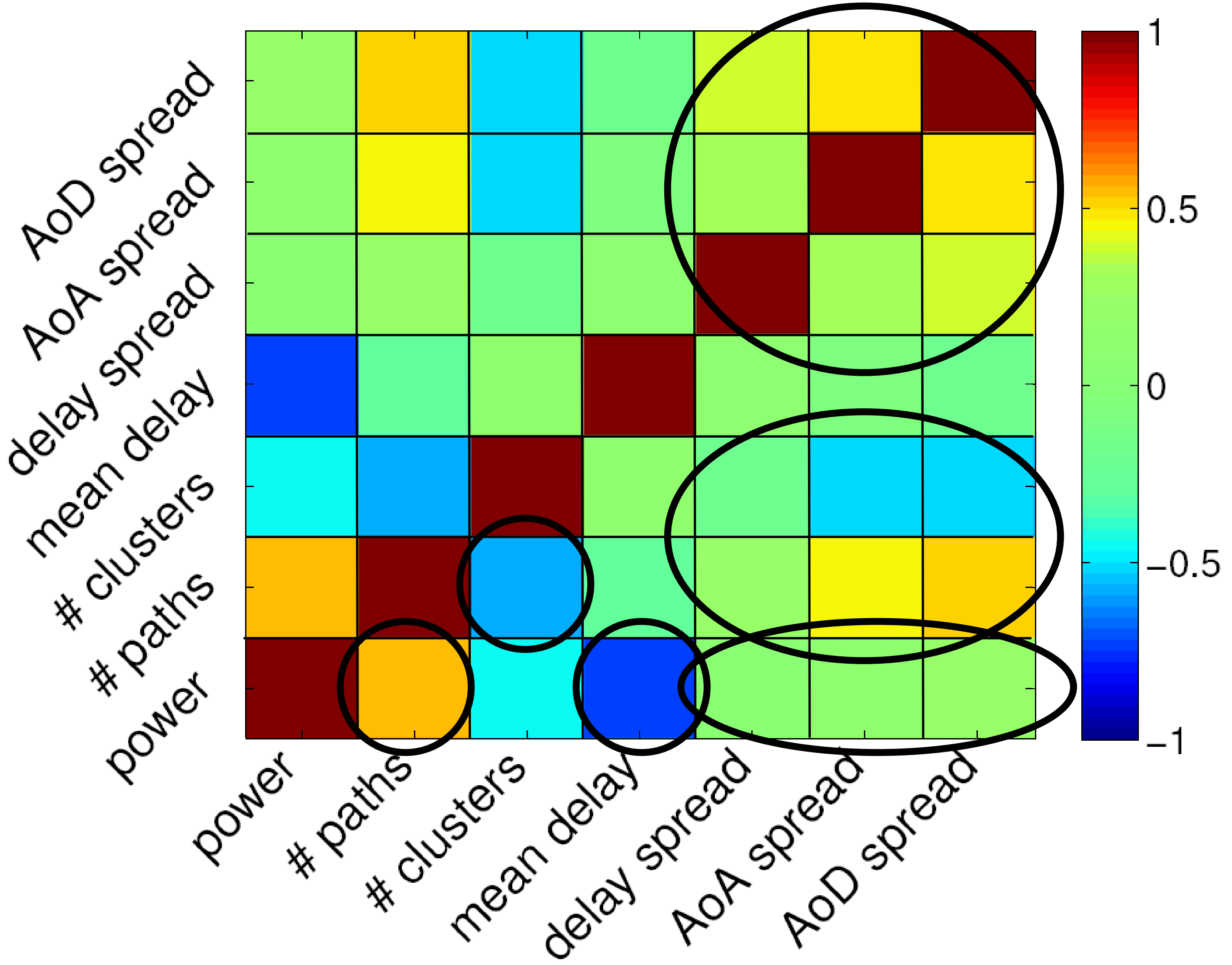


H(t,τ) @ 5.25 GHz: 50 × 32

Cluster parameters for 2.55 GHz in OLOS and LOS

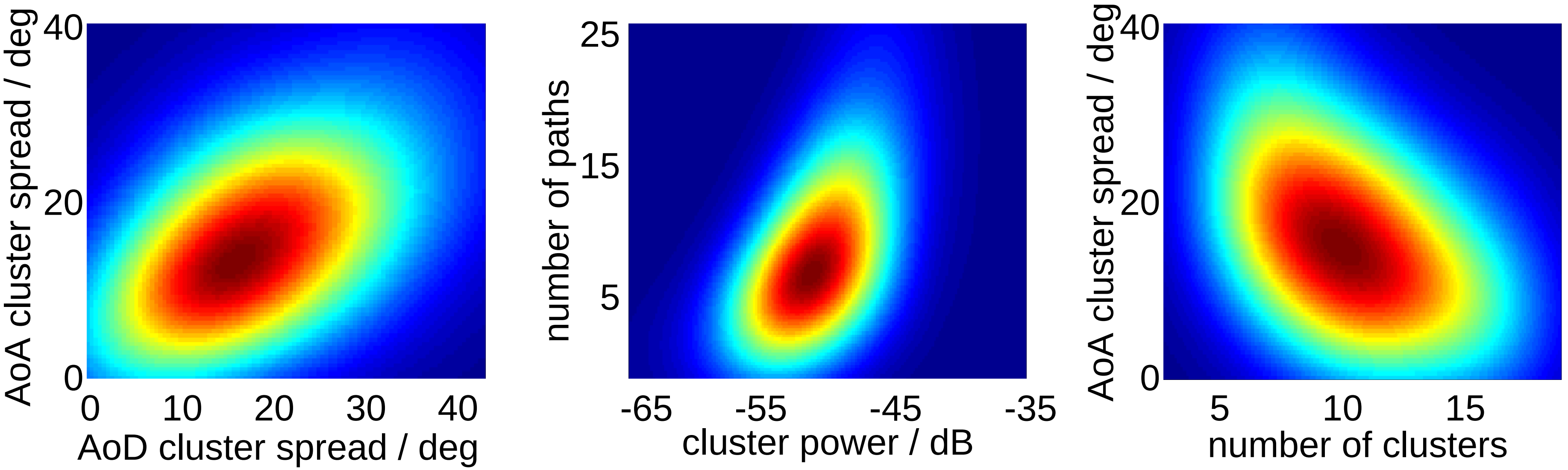


Correlation coefficients



2.55 GHz

Multi-variate distribution of cluster parameters



- The world is not always Gaussian…
- … but sometimes it is a good approximation.

Estimated by Kernel Density Estimator [Ihler] A. Ihler, "Kernel density estimation toolbox for MATLAB." [Online]. Available at http://ssg.mit.edu/ihler/code/kde.shtml

Cluster generation

1. Marginalize the environment pdf to the number of clusters, → draw number of clusters N_c
2. Condition the environment pdf given the (just drawn) number of clusters
3. From this conditioned (new) pdf draw cluster parameters for N_c clusters
4. For each cluster, generate paths within the clusters according to:

Path parameters

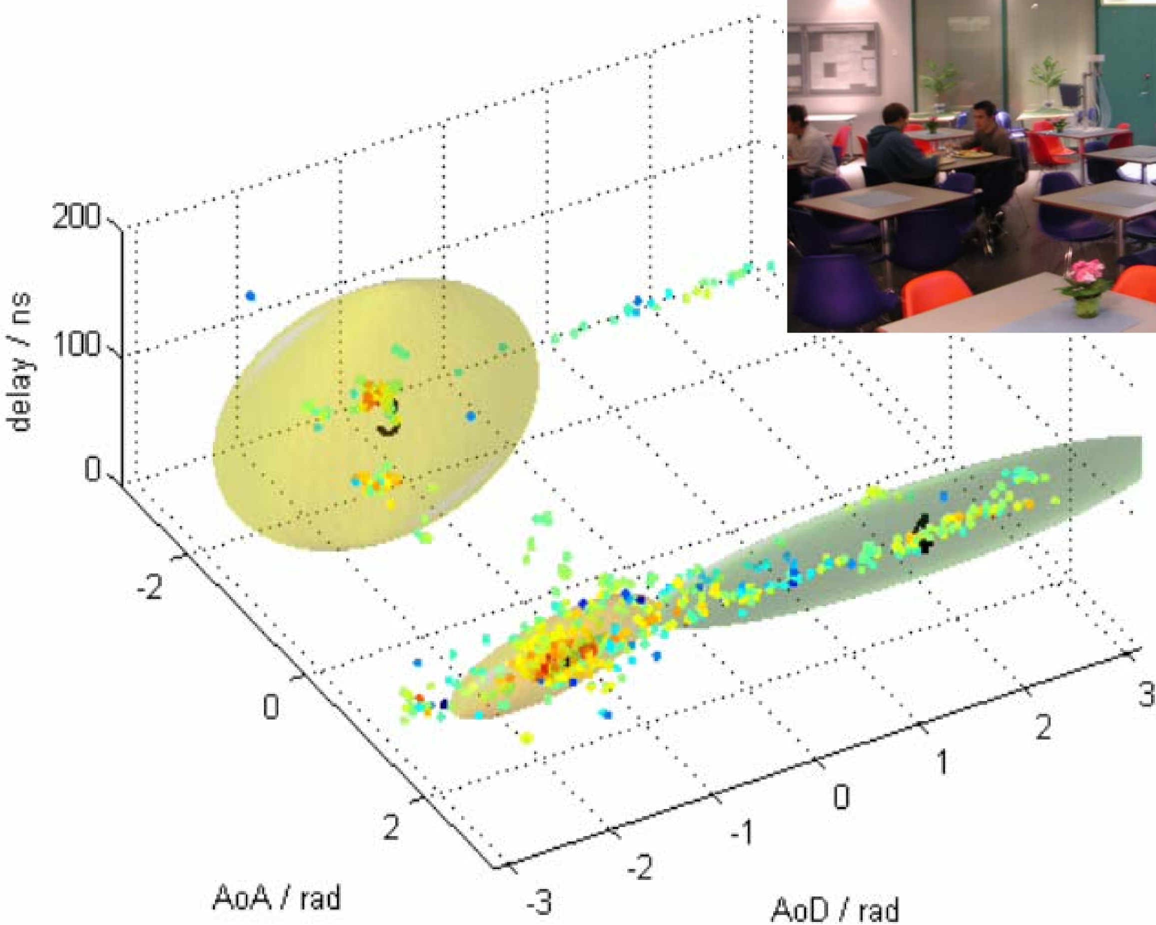
$$
\begin{aligned}
\tau_{cp} &\sim \mathcal{N}(\bar{\tau}_c, \sigma^2_{\tau,c}) \\
\varphi_{\mathsf{Rx},cp} &\sim \mathcal{N}(\bar{\varphi}_{\mathsf{Rx},c}, \sigma^2_{\varphi_{\mathsf{Rx},c}}) \\
\varphi_{\mathsf{Tx},cp} &\sim \mathcal{N}(\bar{\varphi}_{\mathsf{Tx},c}, \sigma^2_{\varphi_{\mathsf{Tx},c}}) \\
\mathsf{abs}(\gamma_{cp}) &= \sqrt{\frac{\bar{\gamma}_c^2}{N_{p,c}}} \\
\mathsf{arg}(\gamma_{cp}) &\sim \mathcal{U}(\,[-\pi \ldots \pi)\,),
\end{aligned}
$$

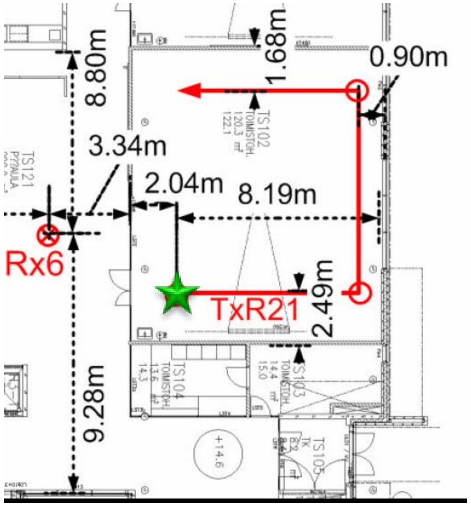
Channel matrix

- Antenna filter:
  - Calculates the phase shifts for each path for a given antenna geometry
- Bandwidth filter
  - Implemented in frequency domain

$$\mathrm{H}(t, \Delta f) = \\ = \sum_{c=1}^{N_c} \sum_{p=1}^{N_{p,c}} \gamma_{cp} \cdot \mathbf{a}_{\mathsf{Rx}}(\varphi_{\mathsf{Rx},cp}, \theta_{\mathsf{Rx},cp}) \mathbf{a}_{\mathsf{Tx}}^{\mathsf{T}}(\varphi_{\mathsf{Tx},cp}, \theta_{\mathsf{Tx},cp}) \cdot \mathrm{e}^{-j2\pi\, \Delta f\, \tau_{cp}}$$

Result from clustering-and-tracking framework





Validation metrics

- Mutual information

$$I(\Delta f, t) = \log_2 \det \left(\mathbf{I}_{N_{\mathsf{Rx}}} + \mathbf{H}_{\mathsf{n}}(\Delta f, t) \mathbf{H}_{\mathsf{n}}(\Delta f, t)^{\mathsf{H}} \right)$$

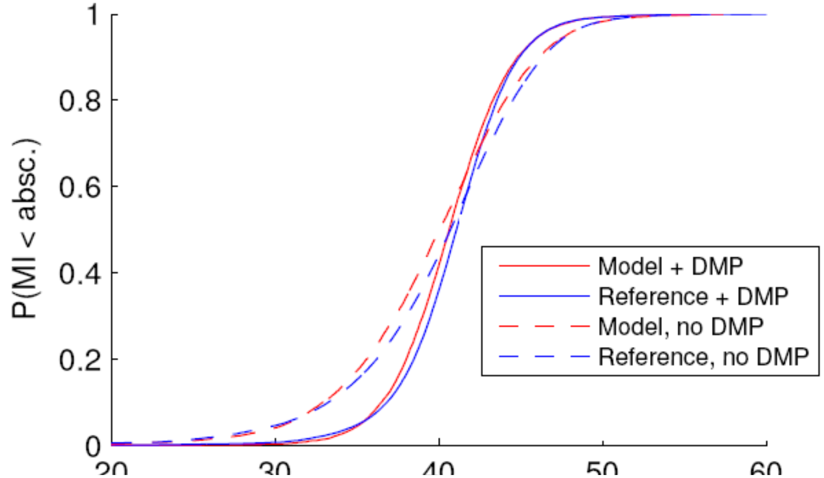
- Environmental Characterization Metric

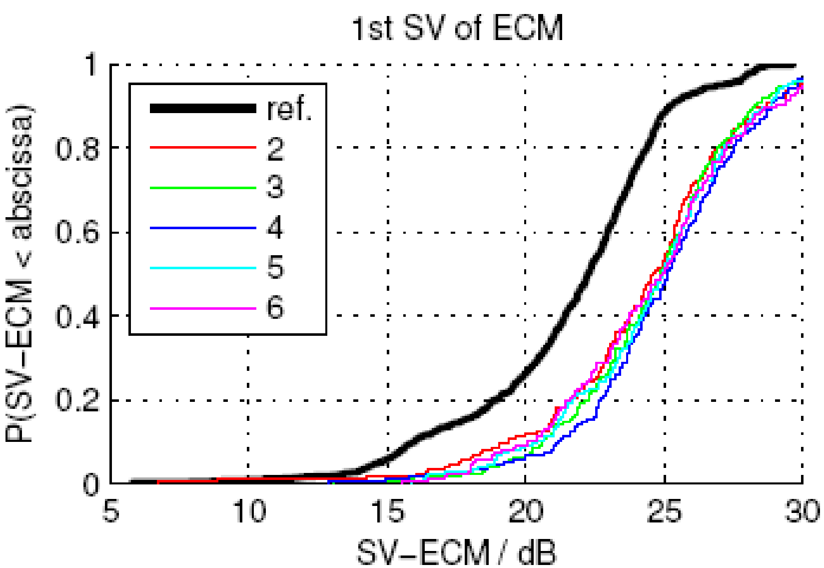
  Czink et al, Wireless Personal Communications, 2008

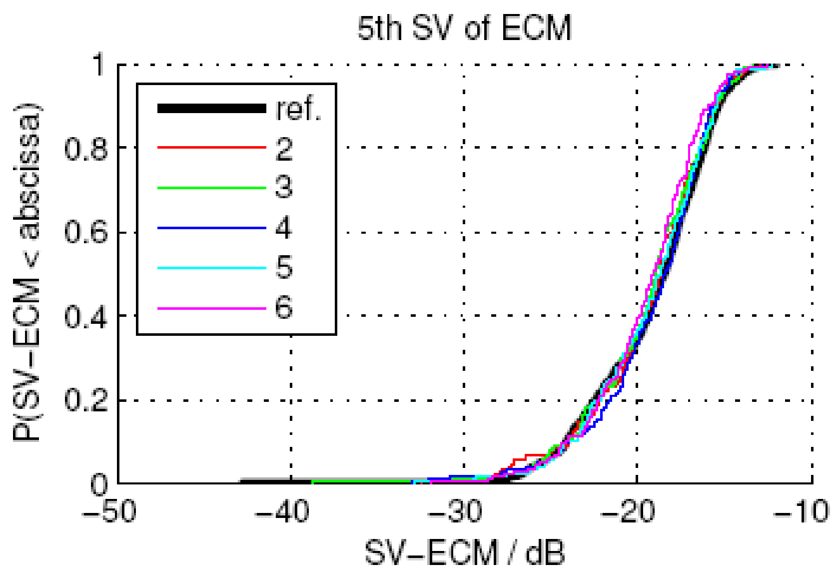
  channel compactness and directivity

- Diversity Metric   Ivrlac and Nossek, ISSPIT 2003

$$D(\boldsymbol{R}) = \mathrm{tr}(\boldsymbol{R}) / ||\boldsymbol{R}||_F$$


P(MI < absc.)
Model + DMP
Reference + DMP
Model, no DMP
Reference, no DMP


1st SV of ECM
P(SV−ECM < abscissa)
ref.
2
3
4
5
6
SV−ECM / dB


5th SV of ECM
P(SV−ECM < abscissa)
ref.
2
3
4
5
6
SV−ECM / dB

Summary – The Random Cluster Model

- Multivariate pdf for ***H*** (Purely Stochastic) =>
  pdf for scatterers (Geometry-based Stochastic) =>
  multivariate pdf for propagation environment (Random-Cluster Model)
- Parameterization by measurements
- Few parameters
- Smooth time variance

- A wealth of novel features
  - Power-weighted clustering
  - Criterion for number of clusters
  - Tracking of clusters
  - Automatic clustering

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Benefits of MIMO

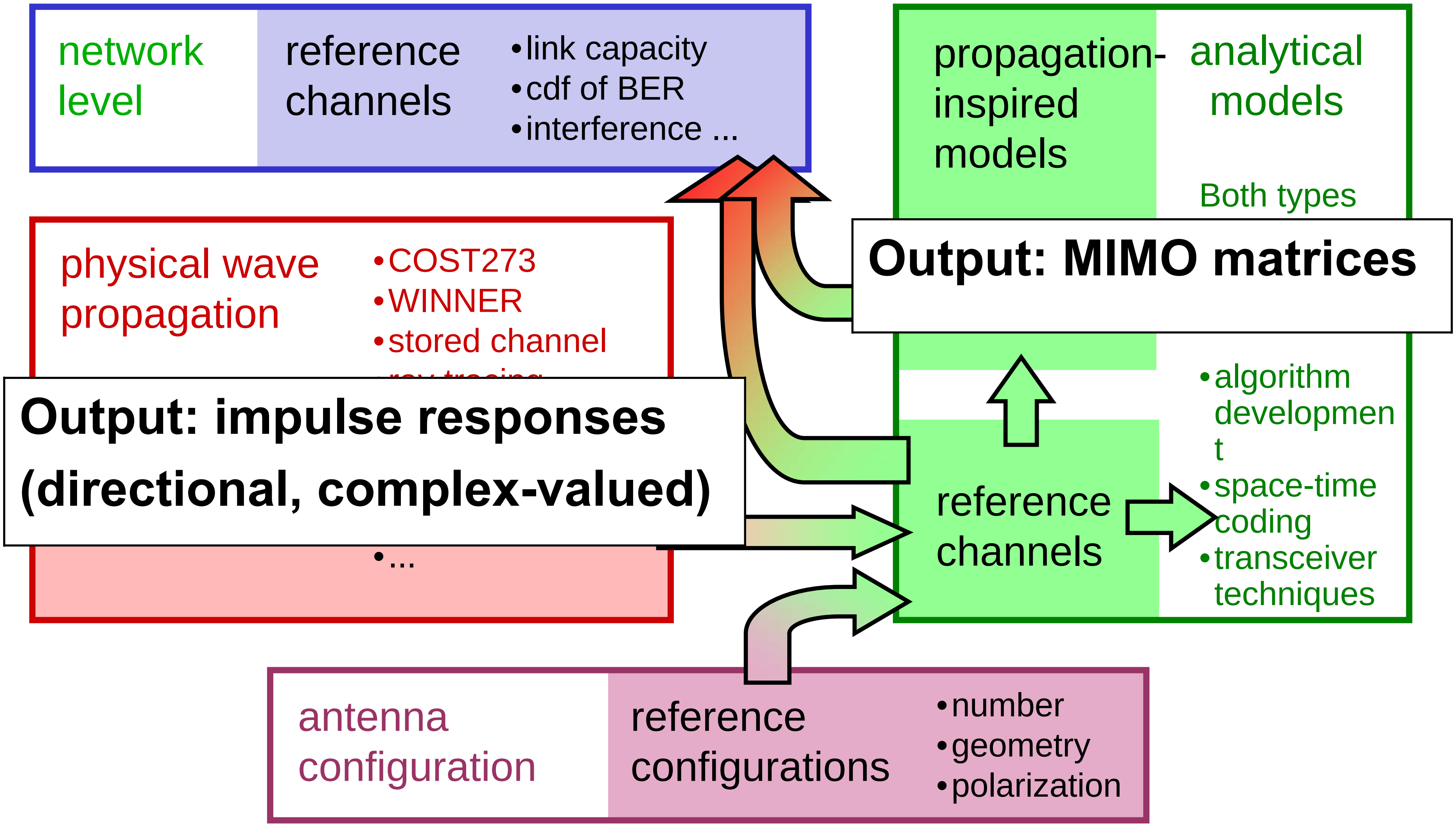
Array Gain
- increase power
- beamforming

But will the propagation channel support what you devise?

Spatial Multiplexing
- multiply data rates
- spatially orthogonal channels

Diversity
- mitigate fading
- space-time coding

Spatial channel models – an overview



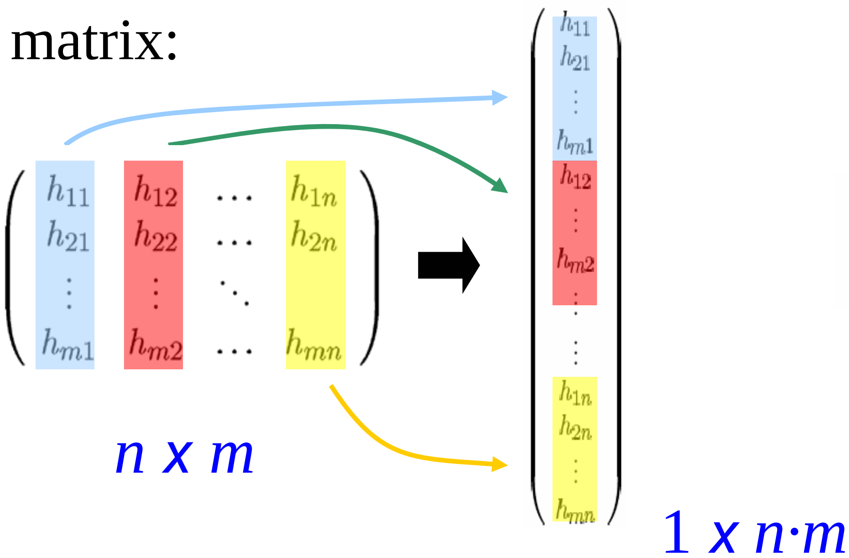
Analytical channel models for MIMO algorithm development

- Analytical model is the proper choice if…
  - RX and TX arrays already specified (n_T,n_R, d, polarization,…)
  - Raw data required:
    Matrix-valued impulse responses

- MIMO theory has been developed with completely random channels in mind („iid model")
- Correlation of TX-RX links changes picture significantly
- Correlation is intimately linked with azimuth power spectra (APSs)

How to deal with correlation

channel matrix:



full channel correlation matrix:

$$\mathbf{R_H} = E\{\mathrm{vec}(\mathbf{H})\mathrm{vec}(\mathbf{H})^H\}$$

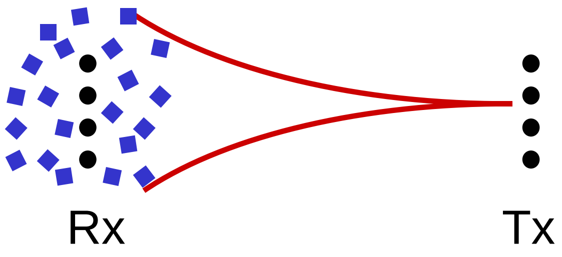
n·m x n·m

- Elements of $\boldsymbol{R_H}$ describe correlation between any pair of **H** elements
- Full description of channel matrix, if channel described by second-order statistics
- Elements of $\boldsymbol{R_H}$ are difficult to interpret physically
- Full correlation matrix is very large =>
- Find meaningful approximations of $\boldsymbol{R_H}$

MIMO > SIMO + MISO!

Look at spatial correlation, the show-stopper of MIMO

- SIMO:
  - only antenna signals available
  - only at one location (Rx)



- MIMO:
  - measure across the link, simultaneously at Tx and Rx
  - correlation between channels
  - phase shift between Tx signals matters

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

Weichselberger et al., IEEE Trans Wireless Comm, 2006

- The [why]-[x]-[sell]-[burger] model has been proven to render mutual information („capacity“) better than any other model so far
- in any environment (in-, outdoor, LOS)
  Lu Dong, PhD, Georgia Tech 2007
- at any frequency (0.3 through 5.8 GHz)
  Wood and Hodgkiss, GLOBECOM 2007
  Eriksson et al., Antenn`06
  Wyne et al., IEEE Trans Vehic. Techn. 2008
- because spatial correlation of individual TX-RX antenna links is accounted for properly
- has been extended to
  - frequency-dispersive channels and
    Costa and Haykin, IEEE Trans. Ant. Prop., 2008
  - time-variant channels
    Weis, Delgaldo, Haardt, WSA `07

Weichselberger Model

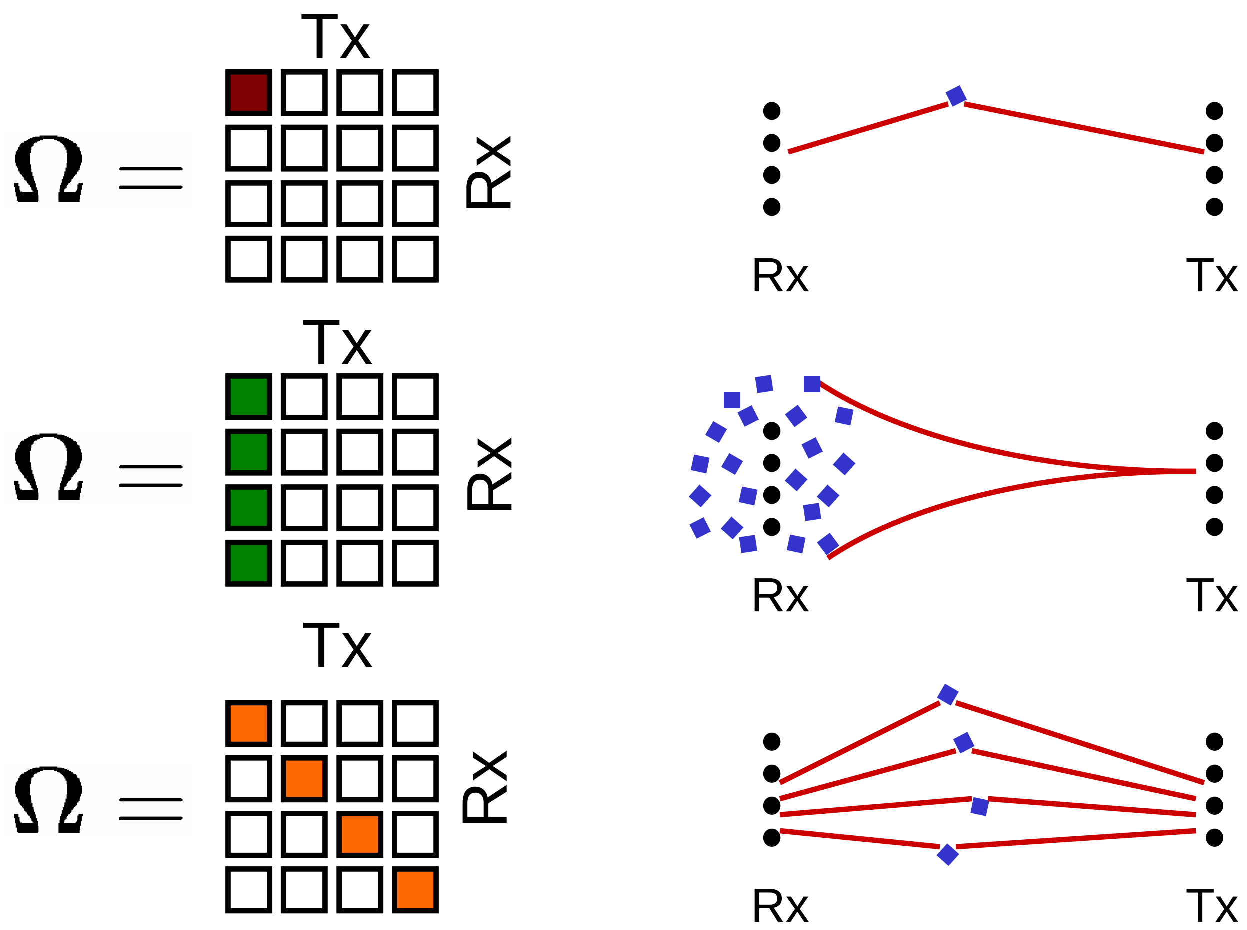
- eigenmodes at Tx-side: $\boldsymbol{U}_{\mathrm{Tx}}$
  $\boldsymbol{M}$ complex basis vectors of size $\boldsymbol{M}_{\mathrm{Tx}}$
- eigenmodes at Rx-side: $\boldsymbol{U}_{\mathrm{Rx}}$
  $\boldsymbol{N}$ complex basis vectors of size $\boldsymbol{M}_{\mathrm{Rx}}$

$$\mathbf{R}_{\mathrm{Rx}} = \mathbf{U}_{\mathrm{Rx}} \mathbf{\Lambda}_{\mathrm{Rx}} \mathbf{U}_{\mathrm{Rx}}^{H}$$
$$\mathbf{R}_{\mathrm{Tx}} = \mathbf{U}_{\mathrm{Tx}} \mathbf{\Lambda}_{\mathrm{Rx}} \mathbf{U}_{\mathrm{Tx}}^{H}$$

$$\boldsymbol{H} = \boldsymbol{U}_{\mathrm{Rx}} \left(\tilde{\boldsymbol{\Omega}} \odot \boldsymbol{G} \right) \boldsymbol{U}_{\mathrm{Tx}}^{\mathrm{T}}$$

Sample Structures of Coupling Matrix

Structure of Ω depends on the environment



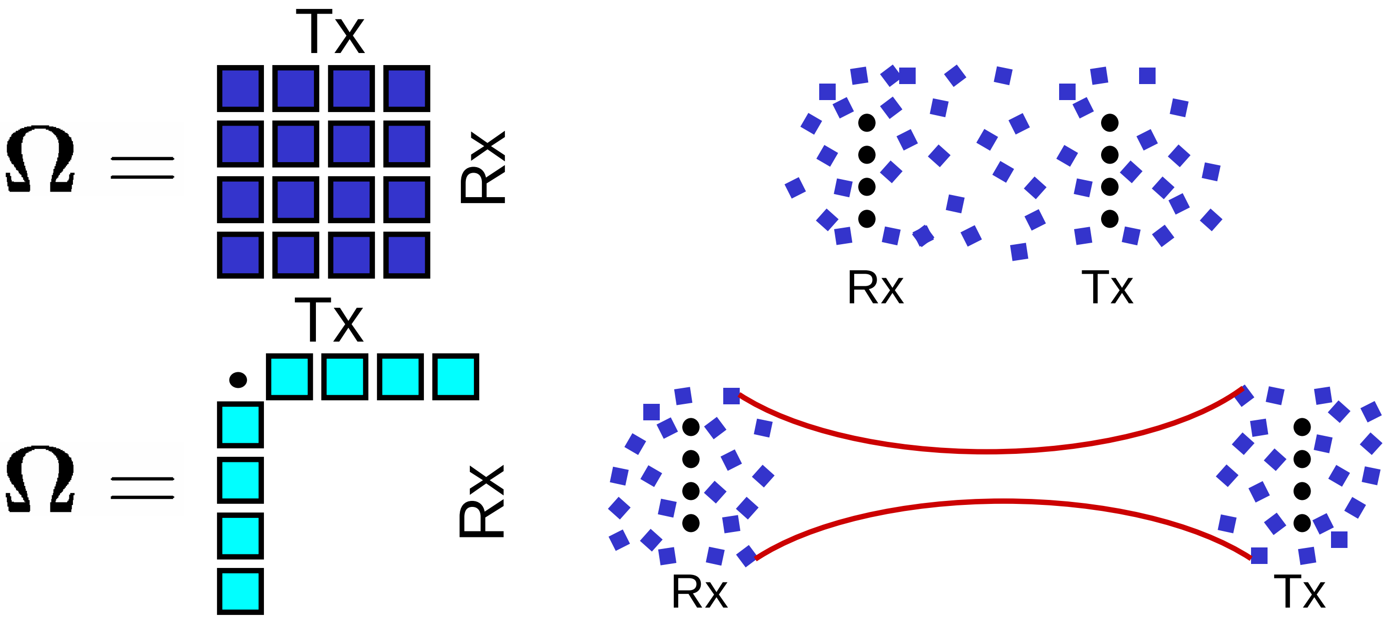
beam-
forming

no spatial
multiplexing
full Rx diversity
no Tx diversity
high Tx
beamforming gain

full spatial multiplexing
Tx separation of streams
possible, but no diversity
on streams

Structure of coupling matrix 2

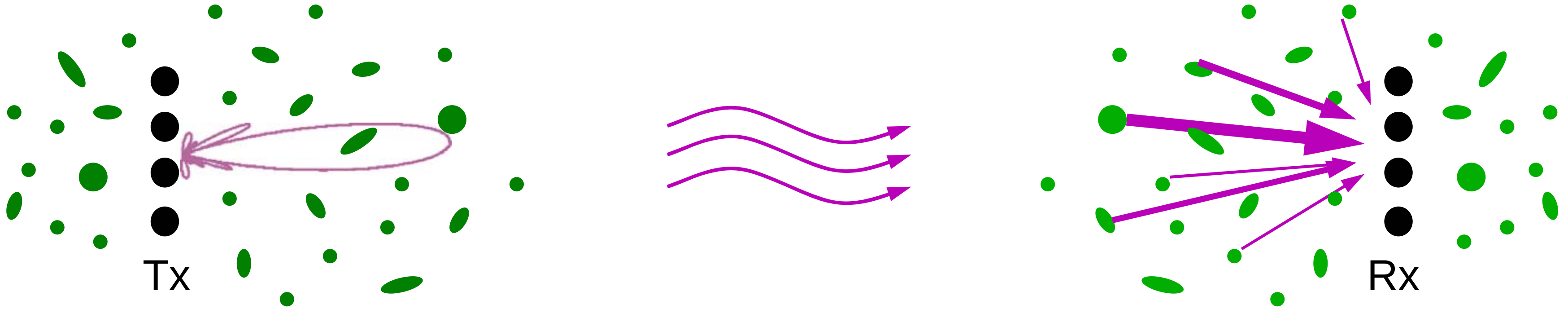
Structure of Ω highly depends on the environment



full rank channel

full rank channel but low rank Ω

Kronecker structure

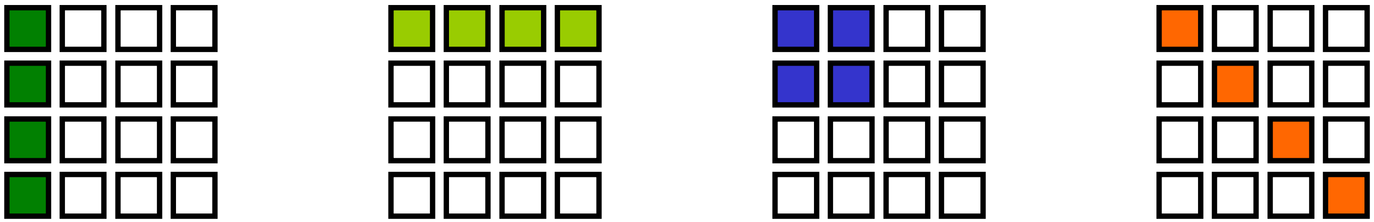


$$\mathrm{E}\left\{\boldsymbol{H}\boldsymbol{x}\boldsymbol{x}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\right\} = c(\boldsymbol{x}) \cdot \boldsymbol{R}_{\mathrm{Rx}}$$

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

Weichselberger model

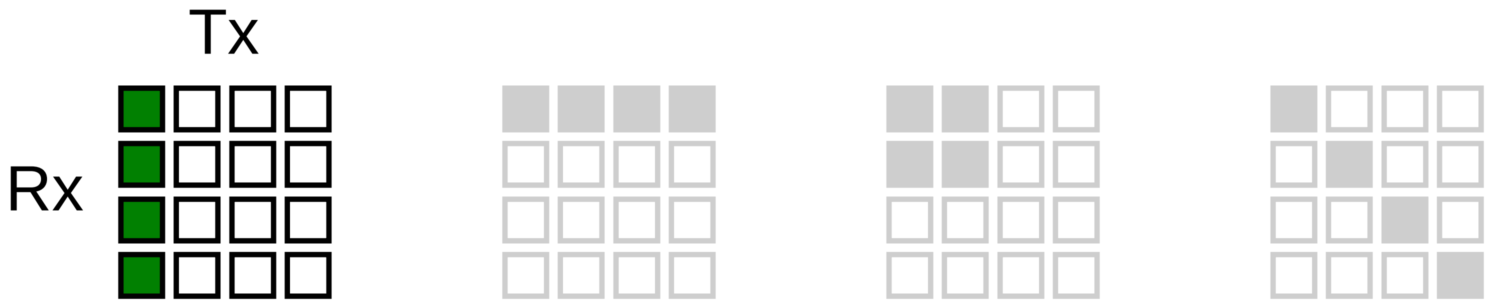
The index of $\omega_{m,n}$ is important:



Even if the eigenvalues are equal in number and in strength, the channel is very different.

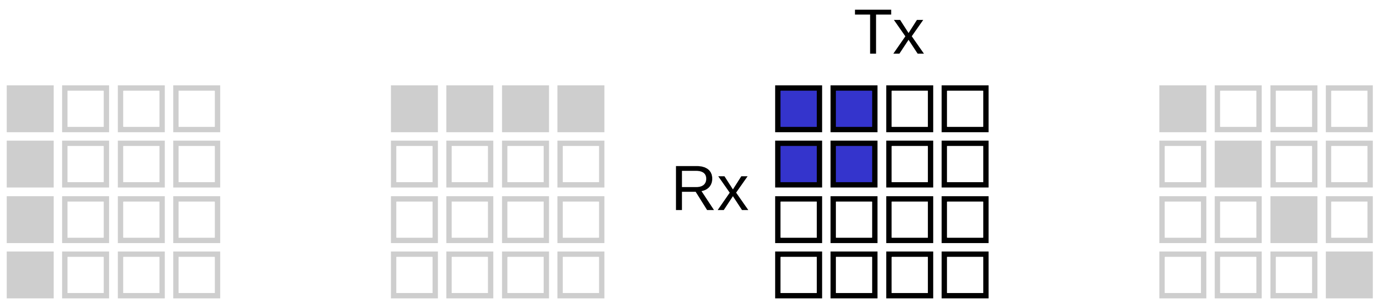
- diversity
- spatial multiplexing
- beamforming gain

Weichselberger model



- no spatial multiplexing
- full Rx diversity
- no Tx diversity
- high Tx beamforming gain

Weichselberger model



- limited spatial multiplexing possible

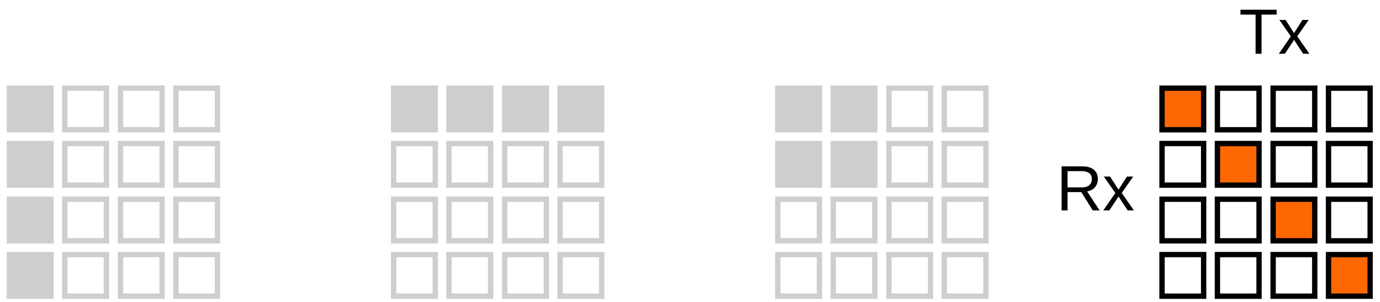
no multiplexing

- limited Rx and Tx diversity
- limited Tx beamforming gain

multi-stream transmission

- full inter-stream diversity
- no Tx separation of streams possible

Weichselberger model



- full spatial multiplexing possible

no multiplexing

- full joint diversity
- no Tx beamforming gain

multi-stream transmission

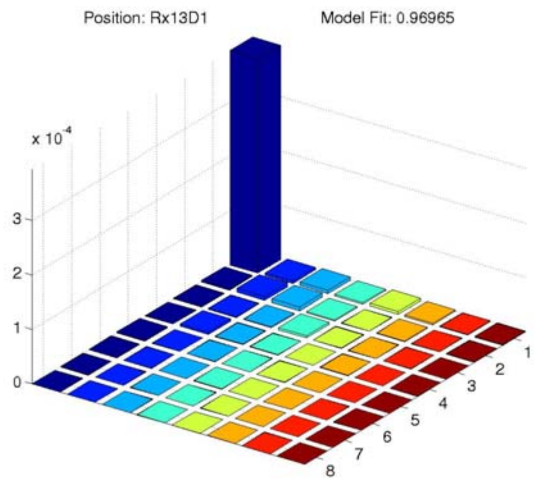
- no diversity on streams
- Tx separation of streams possible

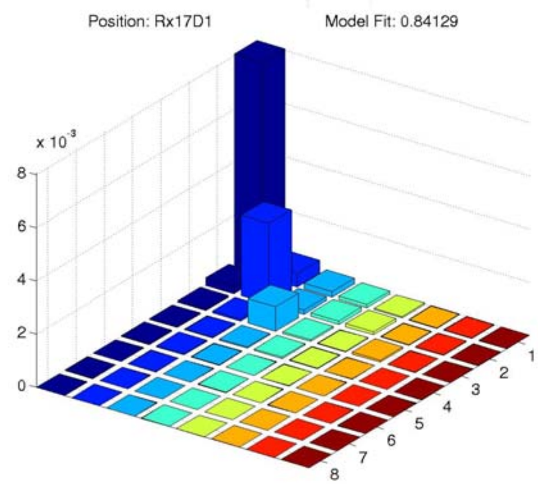
Model Parameter Extraction

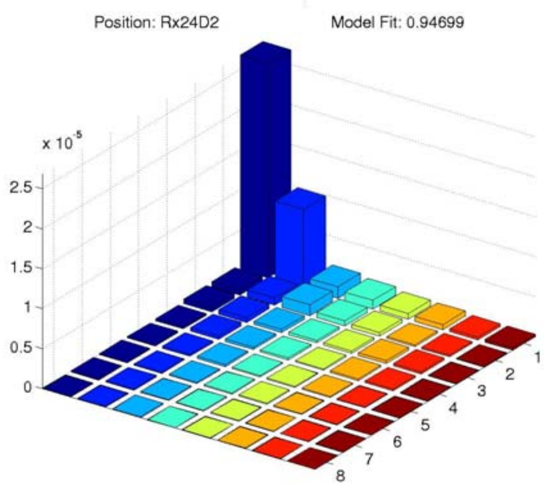
1. Extract model parameters from

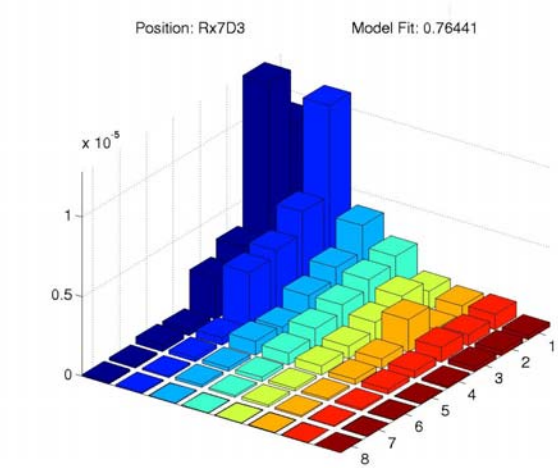
- $$\hat{\mathbf{R}}_{\mathrm{Rx}} = \frac{1}{N}\sum_{i=1}^{N} \mathbf{H}(i)\mathbf{H}(i)^H,$$
- $$\hat{\mathbf{R}}_{\mathrm{Tx}} = \frac{1}{N}\sum_{i=1}^{N} \left[\mathbf{H}(i)^H \mathbf{H}(i)\right]^T$$
- $$\hat{\mathbf{R}}_{\mathrm{Rx}} = \hat{\mathbf{U}}_{\mathrm{Rx}} \hat{\mathbf{\Lambda}}_{\mathrm{Rx}} \hat{\mathbf{U}}_{\mathrm{Rx}}^H$$
- $$\hat{\mathbf{R}}_{\mathrm{Tx}} = \hat{\mathbf{U}}_{\mathrm{Tx}} \hat{\mathbf{\Lambda}}_{\mathrm{Rx}} \hat{\mathbf{U}}_{\mathrm{Tx}}^H$$
- $$\hat{\mathbf{\Omega}}_{weichsel} = \frac{1}{N}\sum_{i=1}^{N} \left(\hat{\mathbf{U}}_{\mathrm{Rx}}^H \mathbf{H}(i) \hat{\mathbf{U}}_{\mathrm{Tx}}^*\right) \odot \left(\hat{\mathbf{U}}_{\mathrm{Rx}}^T \mathbf{H}(i) \hat{\mathbf{U}}_{\mathrm{Tx}}\right)$$
- $$\hat{\mathbf{\Omega}}_{virt} = \frac{1}{N}\sum_{i=1}^{N} \left(\mathbf{A}_{\mathrm{Rx}}^H \mathbf{H}(i) \mathbf{A}_{\mathrm{Tx}}^*\right) \odot \left(\mathbf{A}_{\mathrm{Rx}}^T \mathbf{H}(i) \mathbf{A}_{\mathrm{Tx}}\right)$$

Examples of indoor MIMO situations









MIMO eigenstructure

eigenmodes

$$\boldsymbol{H} = \sum_{k=1}^{M_{\mathrm{Rx}} M_{\mathrm{Tx}}} g_k \sqrt{\lambda_k} \cdot \boldsymbol{U}_k$$

vector-modes

$$\boldsymbol{H} = \sum_{k=1}^{M_{\mathrm{Rx}} M_{\mathrm{Tx}}} g_k \sqrt{\lambda_k} \cdot \boldsymbol{v}_k \boldsymbol{w}_k^{\mathrm{T}}$$

Structured vectormodes - coupling matrix

$$\boldsymbol{H} = \boldsymbol{U}_{\mathrm{Rx}} \left(\tilde{\boldsymbol{\Omega}} \odot \boldsymbol{G} \right) \boldsymbol{U}_{\mathrm{Tx}}^{\mathrm{T}}$$

Kronecker structure

$$\boldsymbol{H} = c \cdot \boldsymbol{R}_{\mathrm{Rx}}^{1/2} \boldsymbol{G} \boldsymbol{R}_{\mathrm{Tx}}^{\mathrm{T}/2}$$

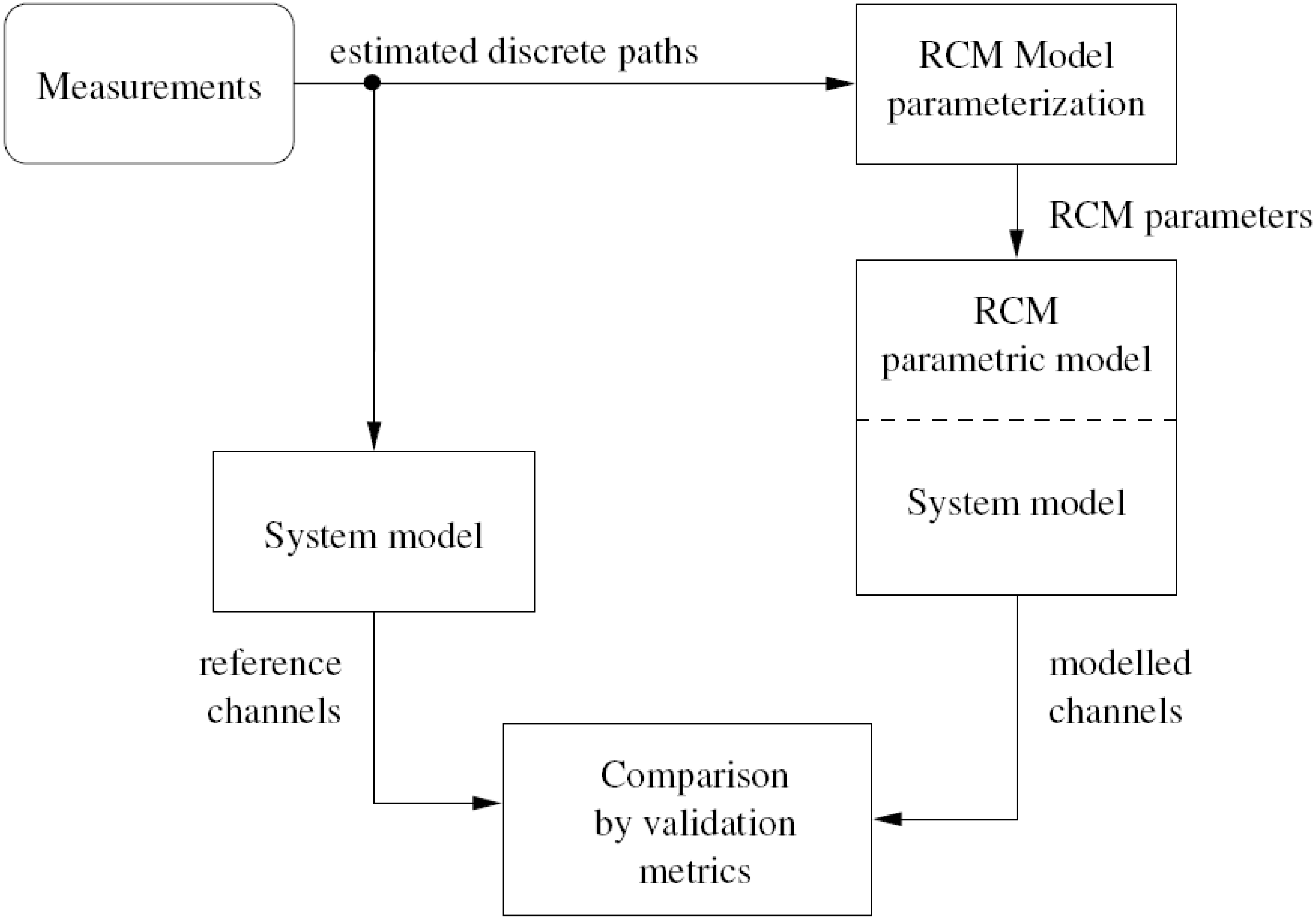
Some suggestions

LTE MIMO algorithms having been developed by mainly stochastic models,

- and will be evaluated by ITU-R M.2135 (essentially WINNER).
- Check them with propagation-oriented models, like the RCM;
- make conformance tests for time-variant channels with RCM;
- obtain stored ***H***-matrices by Weichselberger model.

Thank you!

Validation framework



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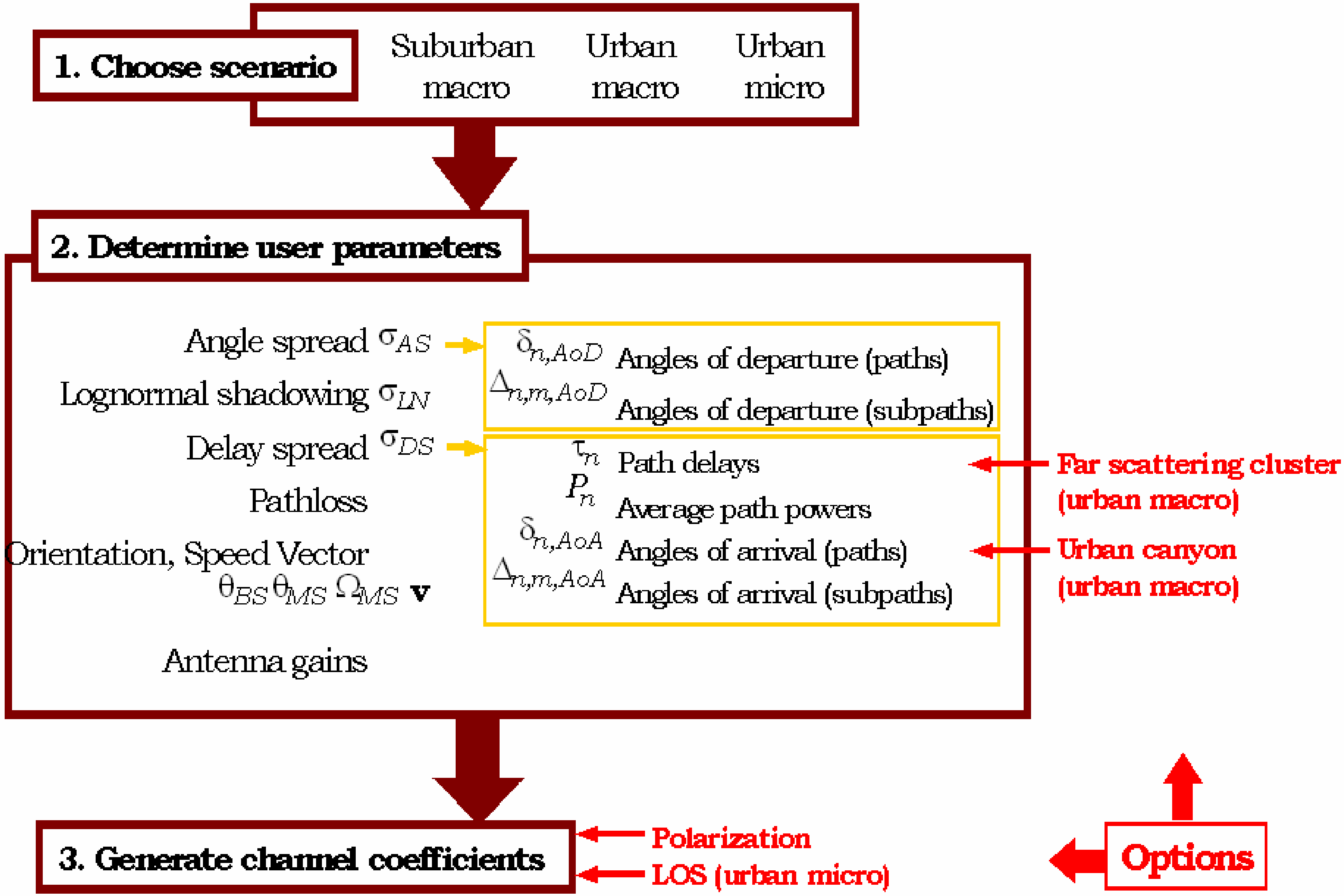
3GPP Spatial Channel Model (SCM)



IEEE 802.11 TGn models

- Focusing on **indoor WLAN** scenarios:
  - 6 different parameter sets
- Channel has a number of taps,
  clusters can **extend over many taps** ☺
  - Cluster power decreases exponentially
- Cluster positions are **prespecified in tables** for each scenario
- Time variance modelled by Doppler statistics
- The channel matrix for each tap is generated using the Kronecker separablity ☹