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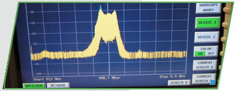


Radio Engineering

Lecture 6: Channel Models

Florian Kaltenberger

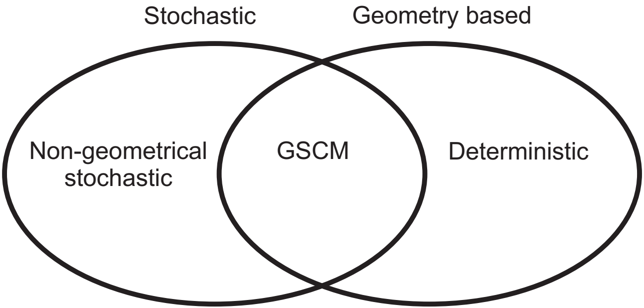
Last lecture

6. Multiple-Input Multiple-Output (MIMO) channels
   - Definitions
   - System model
   - Mutual coupling and correlation
   - Double directional channel characterization
   - Angular power spectra
7. Channel Sounding
   - Time and frequency domain sounding
   - Directionally resolved measurements
   - Parameter estimation methods

This lecture

8. Channel Models
   - Overview
   - Stochastic models
   - Geometry based models
9. Channel Simulation
   - Sampled channels
   - Correlation simulation
   - Geometry based simulation

Channel Model Overview



- Non-geometrical stochastic describe the statistics of the channel via power spectra or correlation function
- Geometry based stochastic channel models (GSCM) describe the environment (scatterer, etc.) in a stochastic way
- Deterministic channel models are either based on Maxwells equations or on stored impulse responses

Narrowband models
Review of properties

Narrowband models contain ”only one” attenuation, which is modeled as a propagation loss, plus large- and small-scale fading.

Path loss: Often proportional to $1/d^n$, where n is the propagation exponent. (n may be different at different distances)

Large-scale fading: Log-normal distribution (normal distr. in dB scale)

Small-scale fading: Rayleig, Rice, Nakagami distributions ... (**not** in dB-scale)

Okumura’s measurements

Extensive measurement campaign in Japan in the 1960’s.

Parameters varied during measurements:

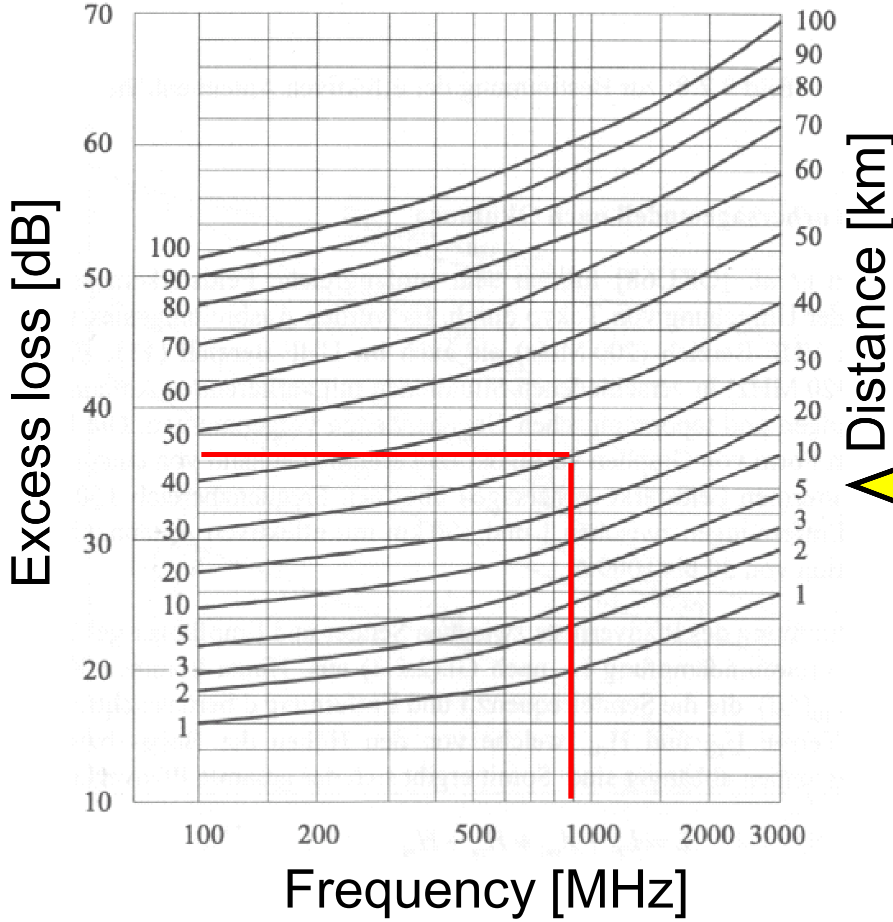
Frequency	100 – 3000 MHz
Distance	1 – 100 km
Mobile station height	1 – 10 m
Base station height	20 – 1000 m
Environment	medium-size city, large city, etc.

Propagation loss is given as **median** values (50% of the time and 50% of the area).

Okumura's measurements excess loss

Example

FIGURE 7.12



These curves are only for h_b=200 m and h_m=3 m

900 MHz and
30 km distance

From [Okumura et al.]

The Okumura-Hata model
How to calculate prop. loss

$$L_{O-H} = A + B\log\left(d_{|km}\right) + C$$

h_b and h_m in meter

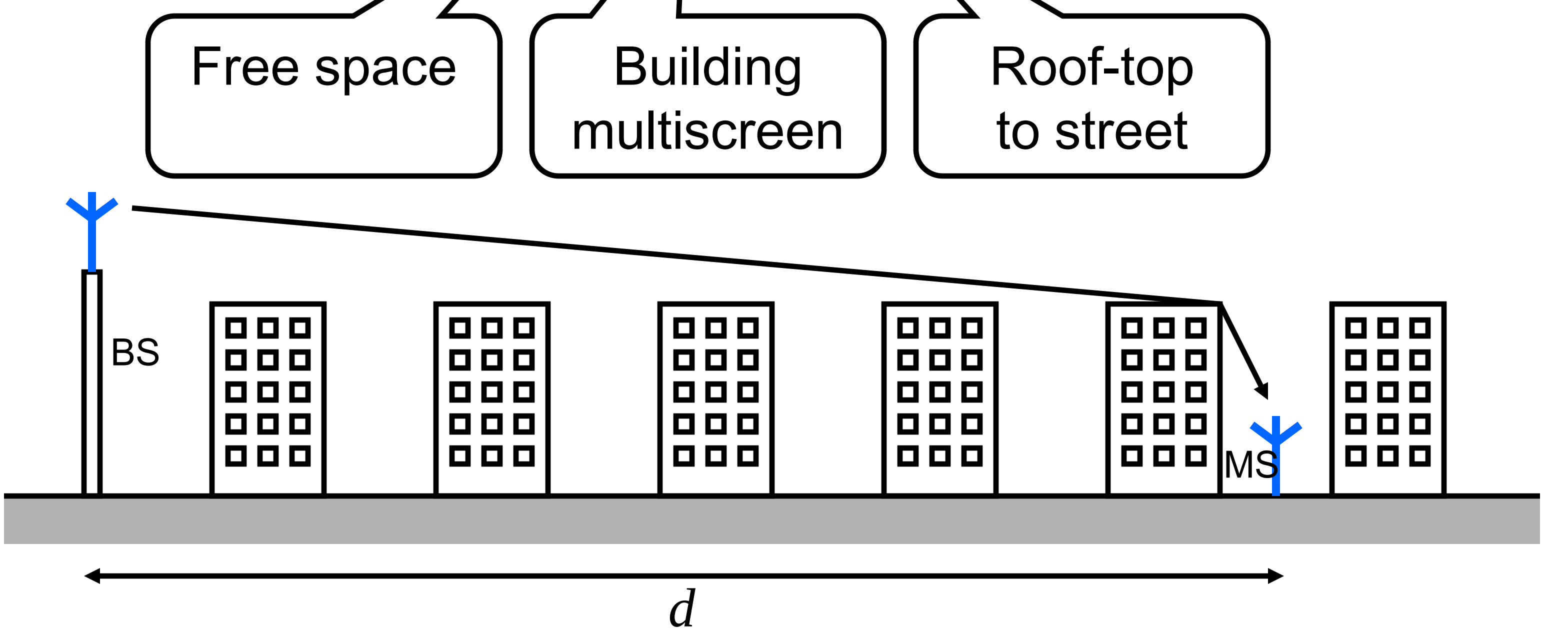
$$A = 69.55 + 26.16\log\left(f_{0|MHz}\right) - 13.82\log\left(h_b\right) - a\left(h_m\right)$$

$$B = 44.9 - 6.55\log\left(h_b\right)$$

	$a\left(h_m\right) =$	$C =$
Metropolitan areas	$8.29\left(\log\left(1.54h_m\right)\right)^2 - 1.1 \quad \text{for} \quad f_0 \le 200 \text{ MHz}$ $3.2\left(\log\left(11.75h_m\right)\right)^2 - 4.97 \quad \text{for} \quad f_0 \ge 400 \text{ MHz}$	0
Small/medium-size cities	$\left(1.1\log\left(f_{0\|MHz}\right) - 0.7\right)h_m - \left(1.56\log\left(f_{0\|MHz}\right) - 0.8\right)$	0
Suburban environments		$-2\left[\log\left(f_{0\|MHz}/28\right)\right]^2 - 5.4$
Rural areas		$-4.78\left[\log\left(f_{0\|MHz}\right)\right]^2 + 18.33\log\left(f_{0\|MHz}\right) - 40.94$

The COST 231-Walfish-Ikegami model
How to calculate prop. loss

$$L = L_0 + L_{msd} + L_{rts}$$



Details about calculations can be found in the textbook, Section 7.6.2.

Motley-Keenan indoor model

For indoor environments, the attenuation is heavily affected by the building structure, walls and floors play an important rule

$$PL = PL_0 + 10n\log(d/d_0) + F_{\text{wall}} + F_{\text{floor}}$$

distance dependent path loss

sum of attenuations from walls, 1-20 dB/wall

sum of attenuation from the floors (often larger than wall attenuation)

site specific, since it is valid for a particular case

Wideband models

- Tapped delay line model often used

$$h(t,\tau)=\sum_{i=1}^{N}\alpha_i(t)\exp\left(j\theta_i(t)\right)\delta(\tau-\tau_i)$$

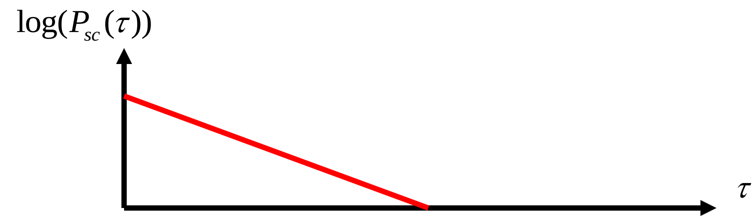
- Often Rayleigh-distributed taps, but might include LOS and different distributions of the tap values
- Mean tap power determined by the power delay profile

Power delay profile

- Often described by a single exponential decay

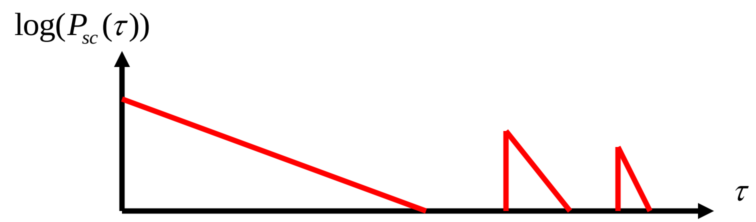
$$P_{sc}(\tau) = \begin{cases} exp(-\tau / S_\tau) & \tau \geq 0 \\ 0 & otherwise \end{cases}$$

delay spread



- though often there is more than one "cluster"

$$P(\tau) = \begin{cases} \sum_k \frac{P_k^c}{S_{\tau,k}^c} P_{sc}(\tau - \tau_{0,k}^c) & \tau \geq 0 \\ 0 & otherwise \end{cases}$$



arrival time

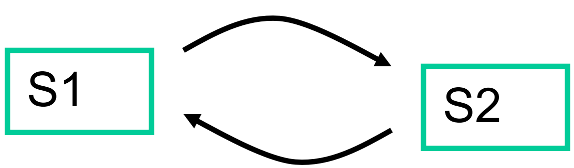
- If the bandwidth is high, the time resolution is large so we might resolve the different multipath components
- Need to model arrival time
- The Saleh-Valenzuela model:

ray arrival time (Poisson)

$$h(\tau) = \sum_{l=0}^{L}\sum_{k=0}^{K}\alpha_{k,l}(\tau)\delta(\tau - T_l - \tau_{k,l})$$

cluster arrival time (Poisson)

- The Δ-K-model:



arrival rate: $\lambda_0(t)$ $K\lambda_0(t)$

Wideband models
COST 207 model for GSM

The COST 207 model specifies:

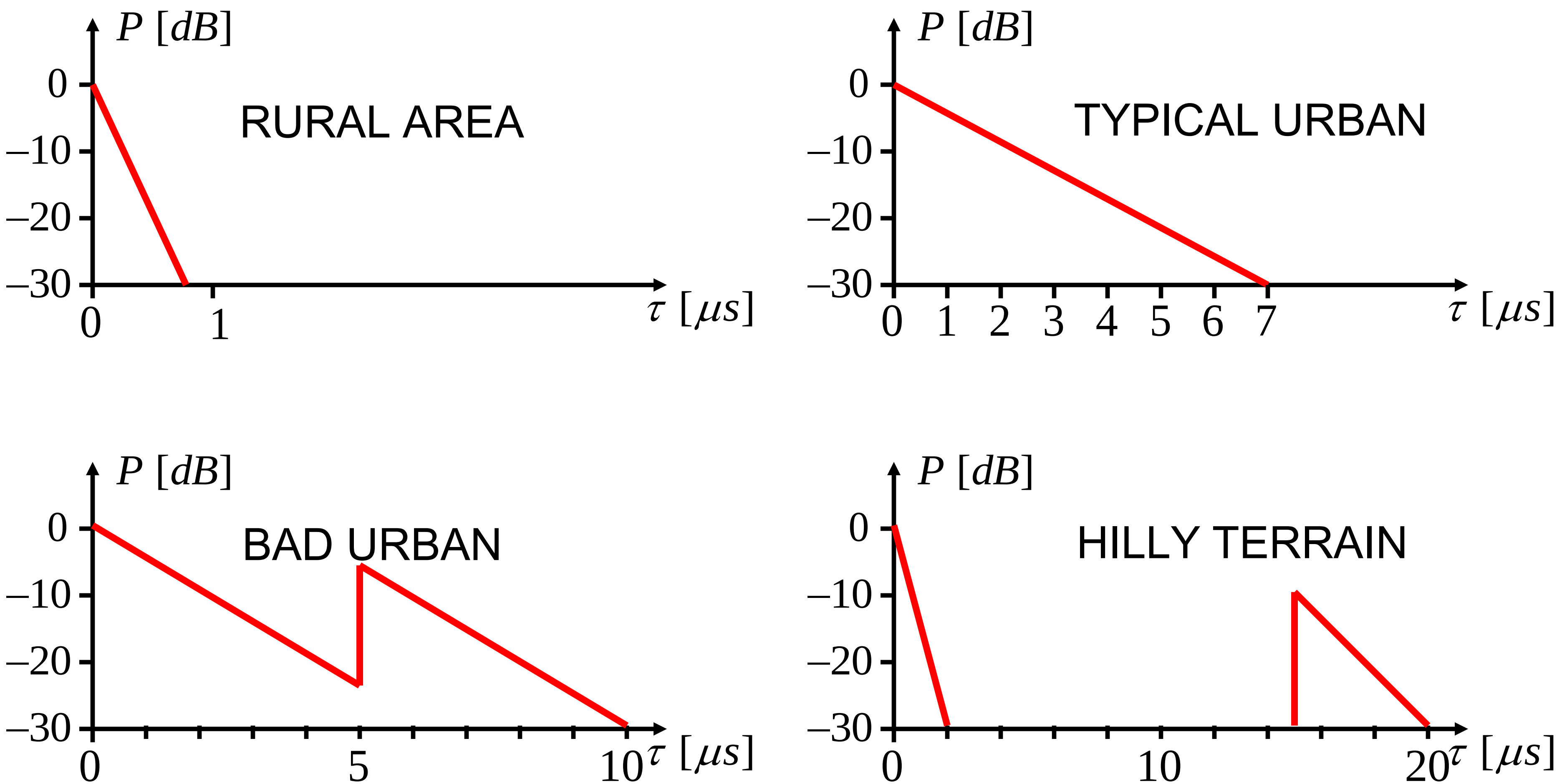
FOUR power-delay profiles for different environments.

FOUR Doppler spectra used for different delays.

IT **DOES NOT** SPECIFY PROAGATION LOSSES FOR THE DIFFERENT ENVIRONMENTS!

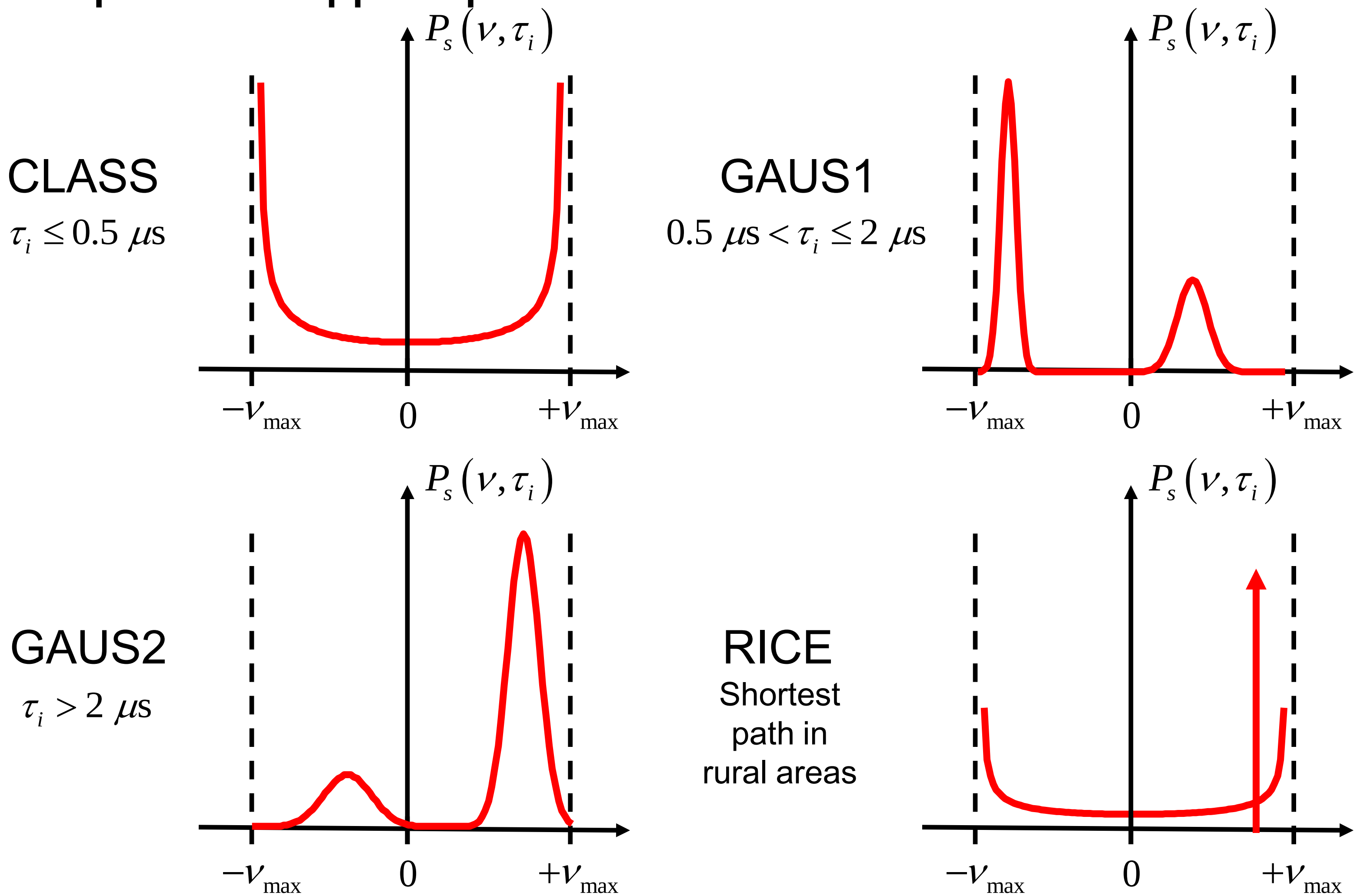
Wideband models
COST 207 model for GSM

Four specified power-delay profiles

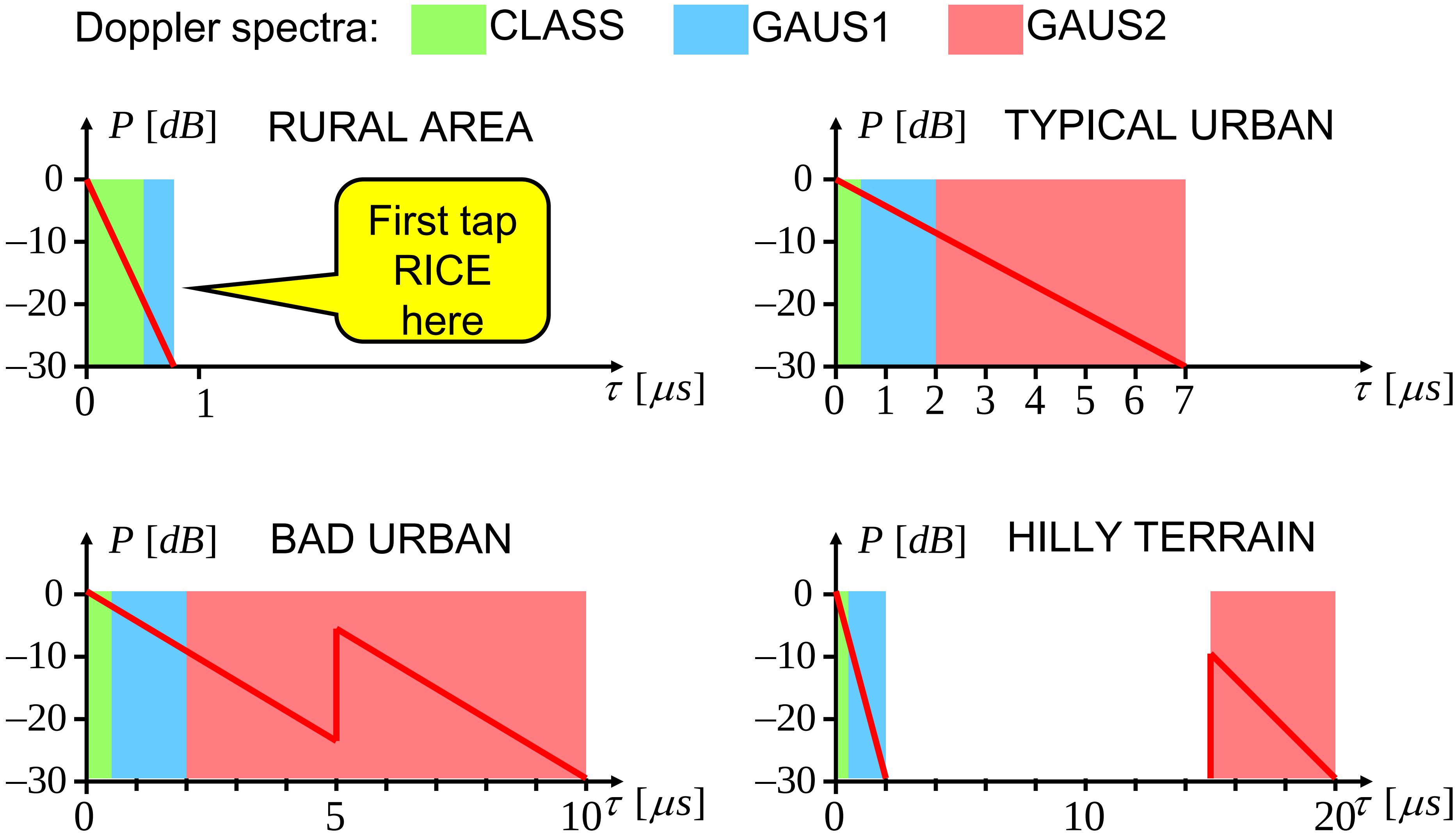


Wideband models
COST 207 model for GSM

Four specified Doppler spectra



Wideband models
COST 207 model for GSM



Wideband models
ITU-R model for 3G

Tap No.	delay/ns	power/dB	delay/ns	power/dB
INDOOR	**CHANNEL A** (50%)		**CHANNEL B** (45%)	
1	0	0	0	0
2	50	-3	100	-3.6
3	110	-10	200	-7.2
4	170	-18	300	-10.8
5	290	-26	500	-18.0
6	310	-32	700	-25.2
PEDESTRIAN	**CHANNEL A** (40%)		**CHANNEL B** (55%)	
1	0	0	0	0
2	110	-9.7	200	-0.9
3	190	-19.2	800	-4.9
4	410	-22.8	1200	-8.0
5			2300	-7.8
6			3700	-23.9
VEHICULAR	**CHANNEL A** (40%)		**CHANNEL B** (55%)	
1	0	0	0	-2.5
2	310	-1	300	0
3	710	-9	8900	-12.8
4	1090	-10	12900	-10.0
5	1730	-15	17100	-25.2
6	2510	-20	20000	-16.0

Stochastic MIMO models

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- Stochastic MIMO models model the correlation matrix $\mathbf{R}_h$
- Can be combined with models for wideband and time-variant channels
- Number of antennas and antenna geometry is predetermined
- Combined modeling of spatial correltation and mutual coupling
- Well suited for testing signal processing algorithms

Stochastic MIMO Models Overview

- iid model ("canonical model")

$$\mathbf{R}_h = \mathbf{I}$$

- Kronecker model

$$\mathbf{R}_h = \mathbf{R}_{Rx} \otimes \mathbf{R}_{Tx}$$

  where $\mathbf{R}_{Rx}$ and $\mathbf{R}_{Tx}$ are the Rx and Tx correlation matrices
- Weichselberger model

$$\mathbf{R}_h = \sum_{i=1}^{N_{Tx}} \sum_{j=1}^{N_{Rx}} \omega_{ji} (\mathbf{u}_{Tx,i} \otimes \mathbf{u}_{Rx,j})(\mathbf{u}_{Tx,i} \otimes \mathbf{u}_{Rx,j})^H$$

  where $\mathbf{u}_{Tx,i}$ and $\mathbf{u}_{Rx,j}$ are the eigenvectors of the Tx and the Rx correlation matrices and ω_{ij} are the elements of the coupling matrix
- Full-correlation model

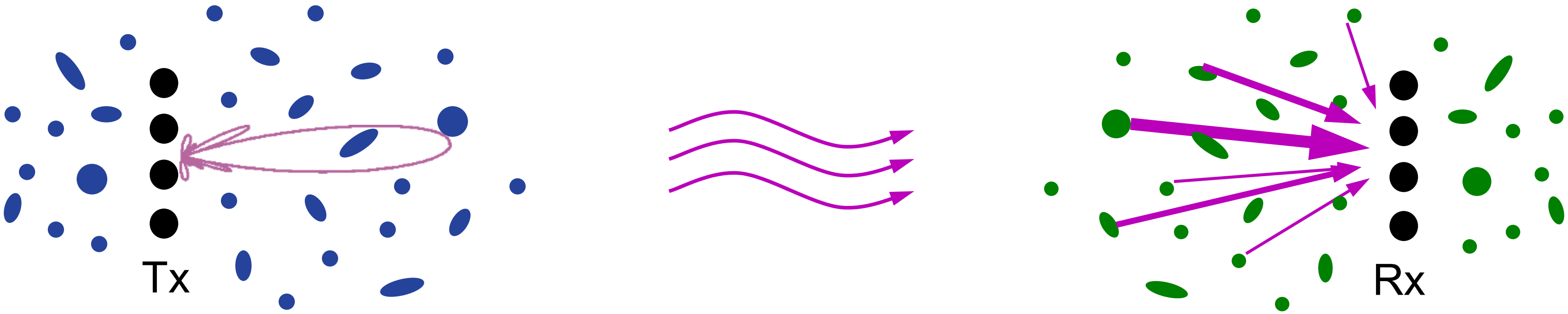
The i.i.d. model

- Simple but not realistic: assume that all elements of $\mathbf{H}(t, \tau)$ are identically and independently distributed (i.i.d)
- Any channel model can be used for the elements (Rayleigh, Ricean, etc.)
- Problems with this model:
  - ignores effects of correlation and mutual coupling
  - overestimates capacity ($rank(\mathbf{H}) = \min(N_{\mathrm{Tx}}, N_{\mathrm{Rx}})$ with probability 1)
  - not verified by measurements

The Kronecker Model

- Treats correlation independently at Tx and Rx
- Transmit correlation matrix: $\mathbf{R}_{Tx} = \mathcal{E}\left\{\mathbf{H}^H\mathbf{H}\right\}$
- Receive correlation matrix: $\mathbf{R}_{Rx} = \mathcal{E}\left\{\mathbf{H}\mathbf{H}^H\right\}$

Kronecker model



- The spatial structure of the MIMO channel is neglected.
- The MIMO channel is described by separated link ends:

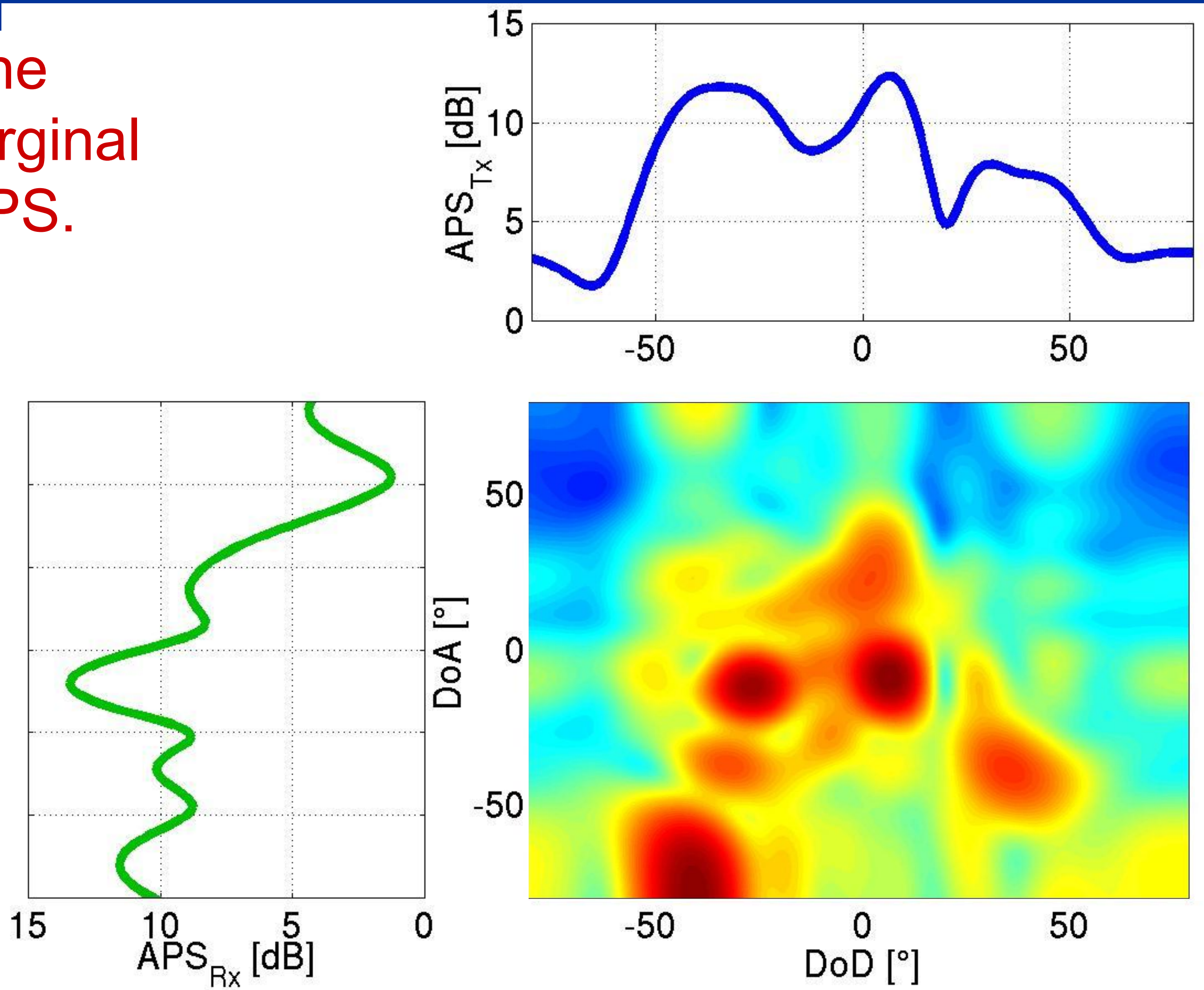
$$\boldsymbol{R}_{\boldsymbol{H}} = c \cdot \boldsymbol{R}_{\mathrm{Tx}} \otimes \boldsymbol{R}_{\mathrm{Rx}} \qquad \boldsymbol{H} = \boldsymbol{R}_{\mathrm{Rx}}^{1/2} \boldsymbol{G} \boldsymbol{R}_{\mathrm{Tx}}^{T/2}$$

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

Kronecker model (cont.)

Joint APS is the product of marginal Rx- and Tx-APS.

measurement



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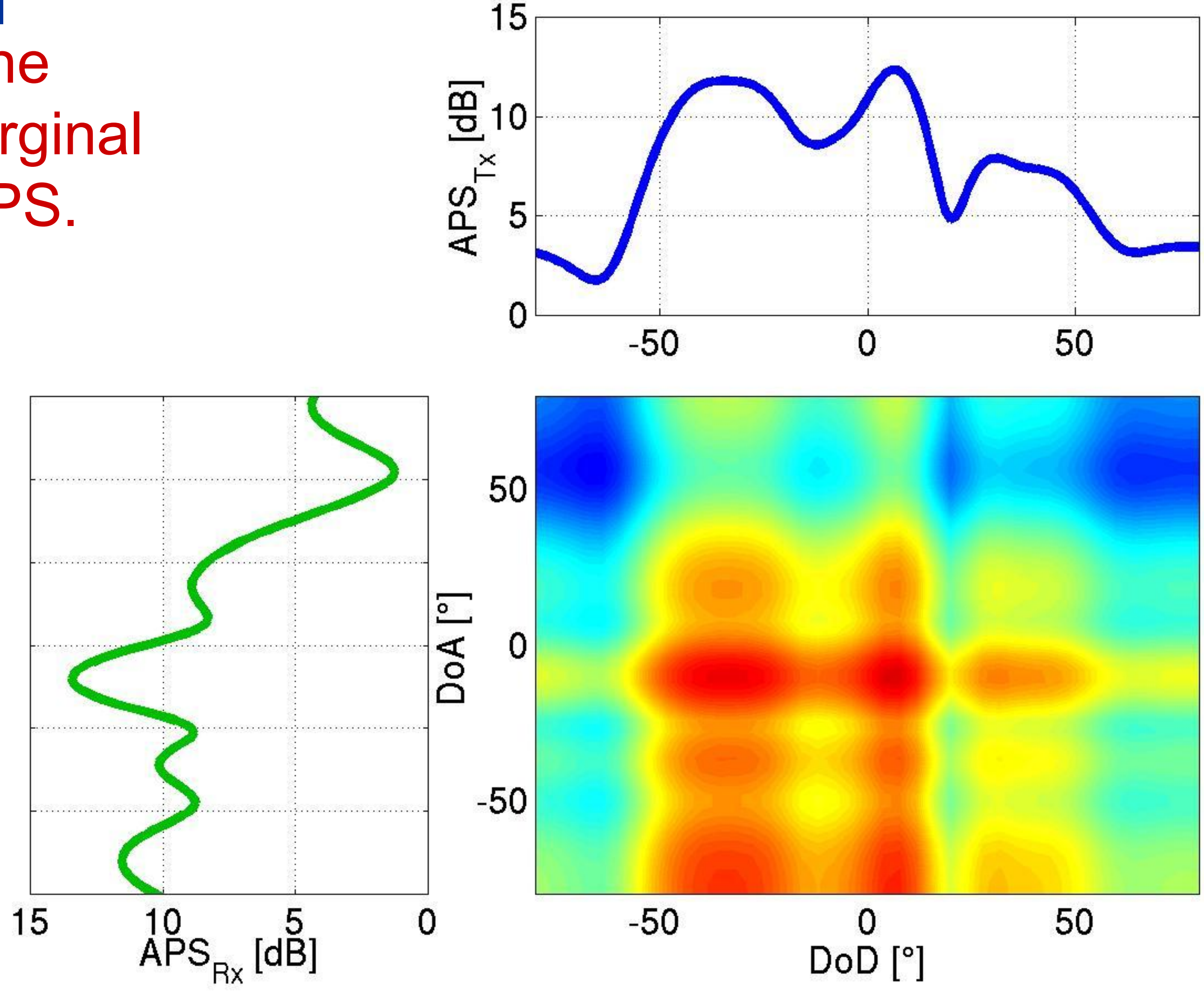
Kronecker model (cont.)

Joint APS is the product of marginal Rx- and Tx-APS.

Kronecker approximation



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Weichselberger Model – Definition

- **Relaxes assumptions of Kronecker model by using power coupling of Tx and Rx eigenmodes, defined by**

$$\mathbf{R}_{\mathsf{Tx}} = \underbrace{\mathbf{U}_{\mathsf{Tx}}}_{\text{Tx eigenmodes}} \mathbf{\Lambda}_{\mathsf{Tx}} \mathbf{U}_{\mathsf{Tx}}^{H} \qquad \mathbf{R}_{\mathsf{Rx}} = \underbrace{\mathbf{U}_{\mathsf{Rx}}}_{\text{Rx eigenmodes}} \mathbf{\Lambda}_{\mathsf{Rx}} \mathbf{U}_{\mathsf{Rx}}^{H}$$

- **Power coupling of eigenmodes is described by coupling matrix**

$$\mathbf{\Omega}_{\mathsf{WB}} = \mathrm{E}\left\{ \left(\mathbf{U}_{\mathsf{Rx}}^{H} \mathbf{H} \mathbf{U}_{\mathsf{Tx}}^{*} \right) \odot \left(\mathbf{U}_{\mathsf{Rx}}^{T} \mathbf{H} \mathbf{U}_{\mathsf{Tx}} \right) \right\}$$

- **Channel correlation matrix is modelled as**

$$\mathbf{R}_{\mathbf{h}} = \sum_{i=1}^{M_{\mathrm{T}}} \sum_{j=1}^{M_{\mathrm{R}}} \omega_{ji} (\mathbf{u}_{\mathsf{Tx},i} \otimes \mathbf{u}_{\mathsf{Rx},j})(\mathbf{u}_{\mathsf{Tx},i} \otimes \mathbf{u}_{\mathsf{Rx},j})^{H}, \quad \text{with} \ \ \omega_{ji} = (\mathbf{\Omega}_{\mathsf{WB}})_{j,i}$$

- **Channel realizations can be generated by**

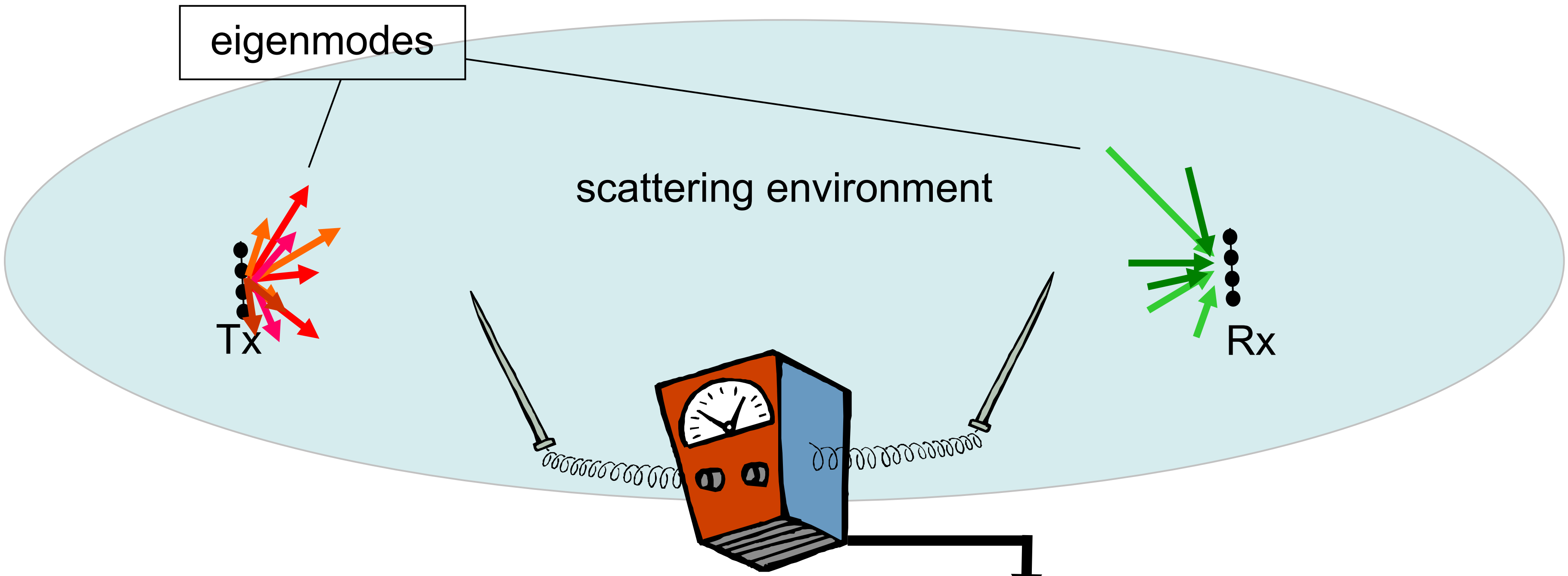
$$\mathbf{H} = \mathbf{U}_{\mathsf{Rx}} (\tilde{\mathbf{\Omega}}_{\mathsf{WB}} \odot \mathbf{G}) \mathbf{U}_{\mathsf{Tx}}^{T},$$

where $\tilde{\Omega}_{\mathsf{WB}}$ is element-wise square-root of Ω_{WB}, and $\mathbf{G} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$

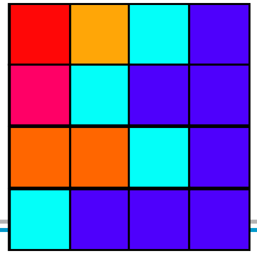
$\odot$ … element-wise matrix product (Hadamard product)

Weichselberger Model – Parameters

What are "eigenmodes" and the coupling matrix Ω_{WB}?



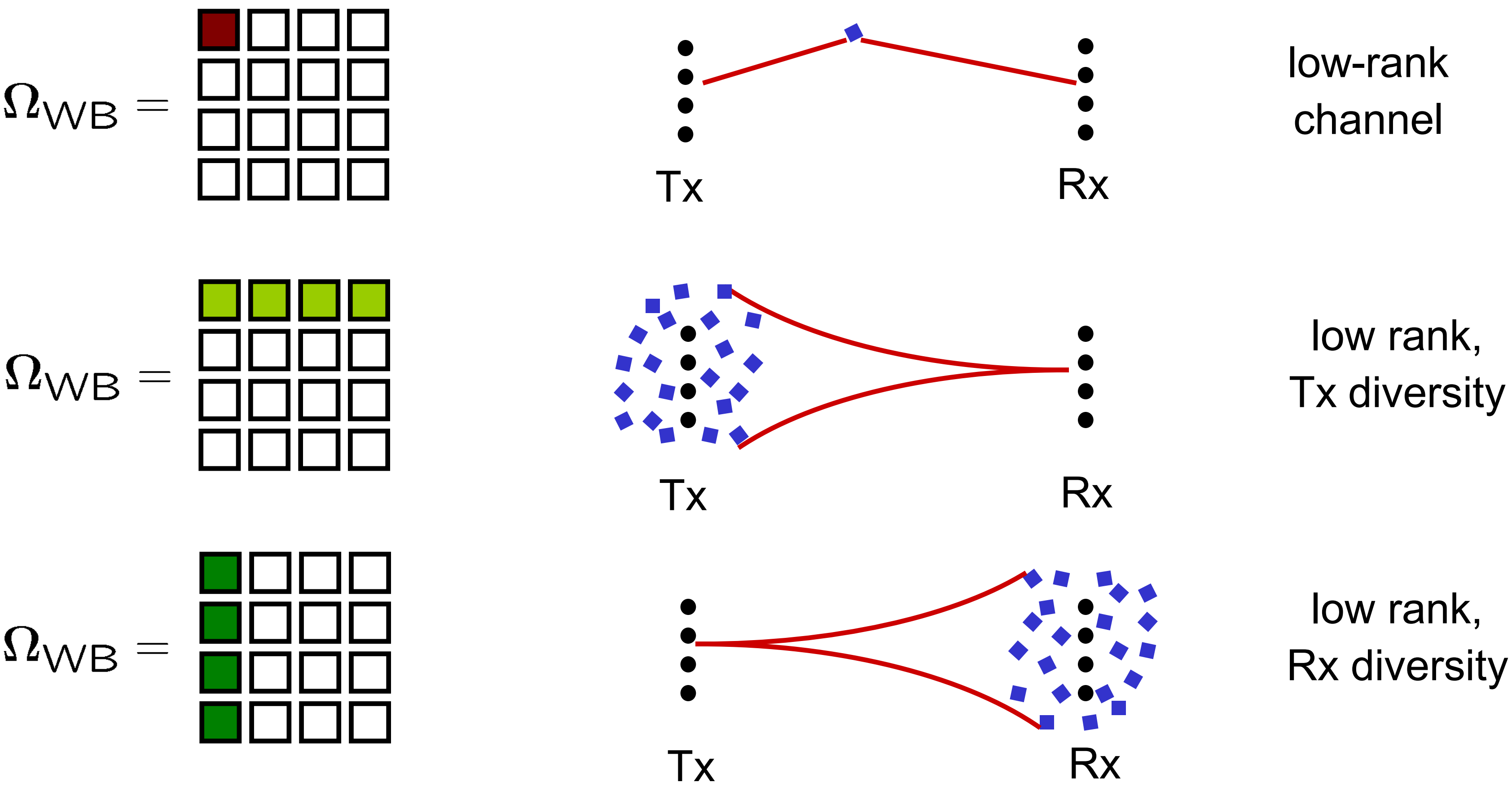
Coupling matrix $\Omega_{\mathrm{WB}} =$



hot … strong power
cold .. weak power

Weichselberger Model – Coupling Matrix (1)

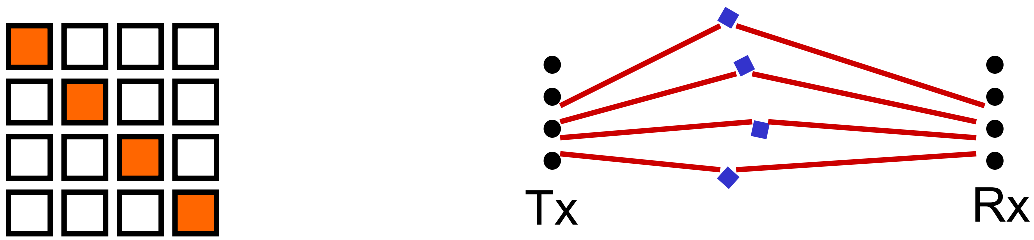
Structure of Ω_{WB} strongly depends on the environment:



Weichselberger Model – Coupling Matrix (2)

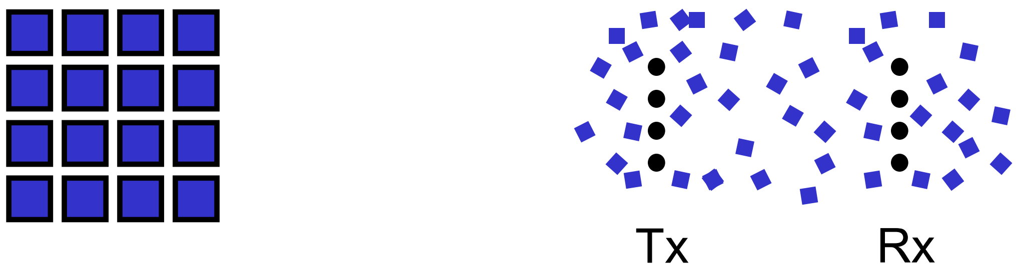
Structure of Ω_{WB} strongly depends on the environment:

$\Omega_{WB} =$



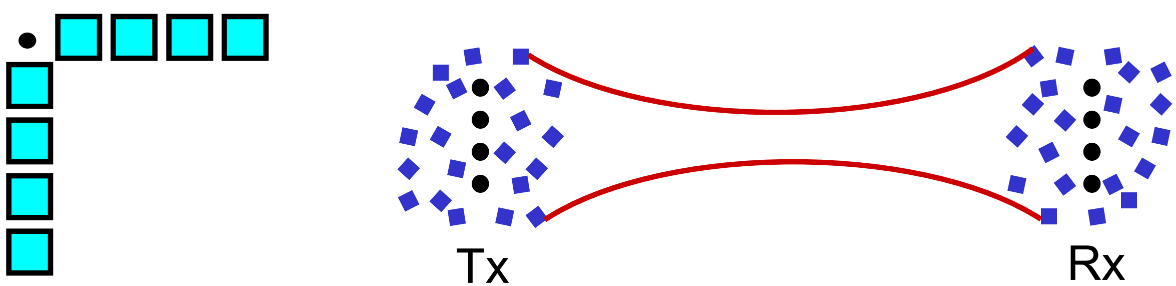
full rank,
no diversity

$\Omega_{WB} =$



full rank,
full diversity

$\Omega_{WB} =$



full rank,
Kronecker

Stochastic MIMO models summary

- Full-correlation model
  - Very complex
  - Most accurate
- Weichselberger model
  - Good approximation
  - Good performance-complexity compromise
- Kronecker model
  - Separates channel into Tx and Rx sides
  - Very popular
  - Very limited validity
- iid model
  - Most simple
  - No physical relevance

Stochastic MIMO model example

- 3GPP specifies four simplified Spatial Channel Models (SCM) for link level evaluations
- See 3GPP TR 25.814 V7.1.0, Section 7.1.3

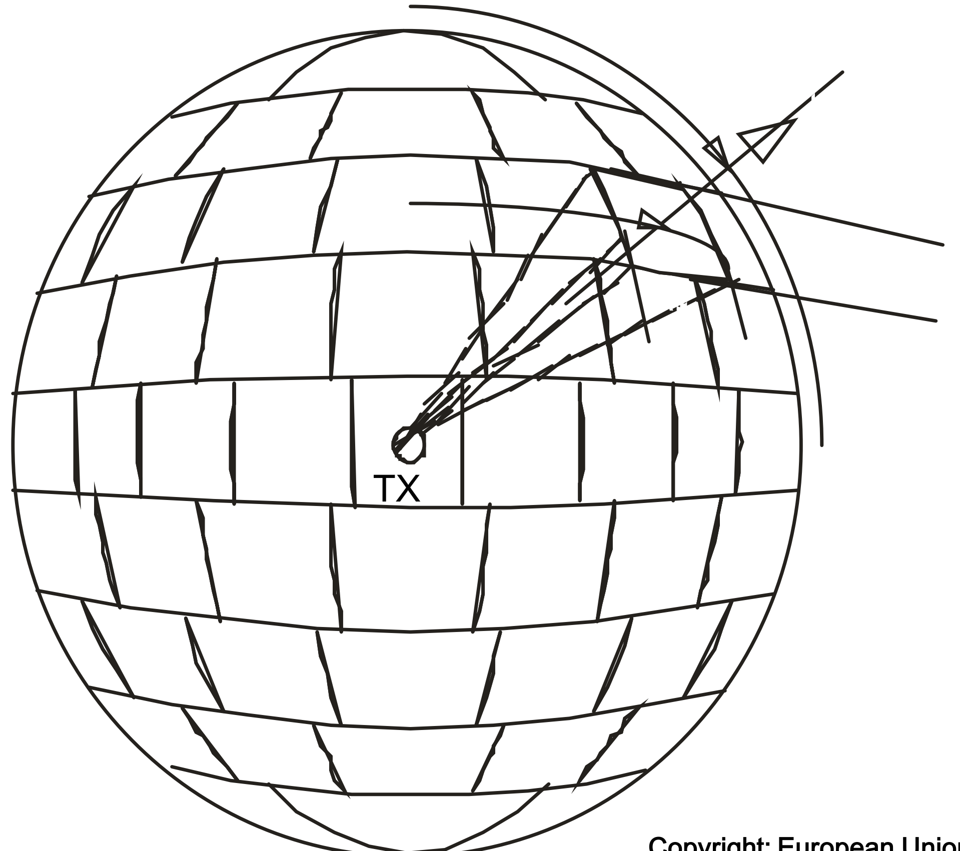
Deterministic modeling methods

- Solve Maxwell's equations with boundary conditions
- Problems:
  - Data base for environment
  - Computation time
- "Exact" solutions
  - Method of moments
  - Finite element method
  - Finite-difference time domain (FDTD)
- High frequency approximation
  - All waves modeled as rays that behave as in geometrical optics
  - Refinements include approximation to diffraction, diffuse scattering, etc.

Ray launching

Rays are launched from TX into discrete directions

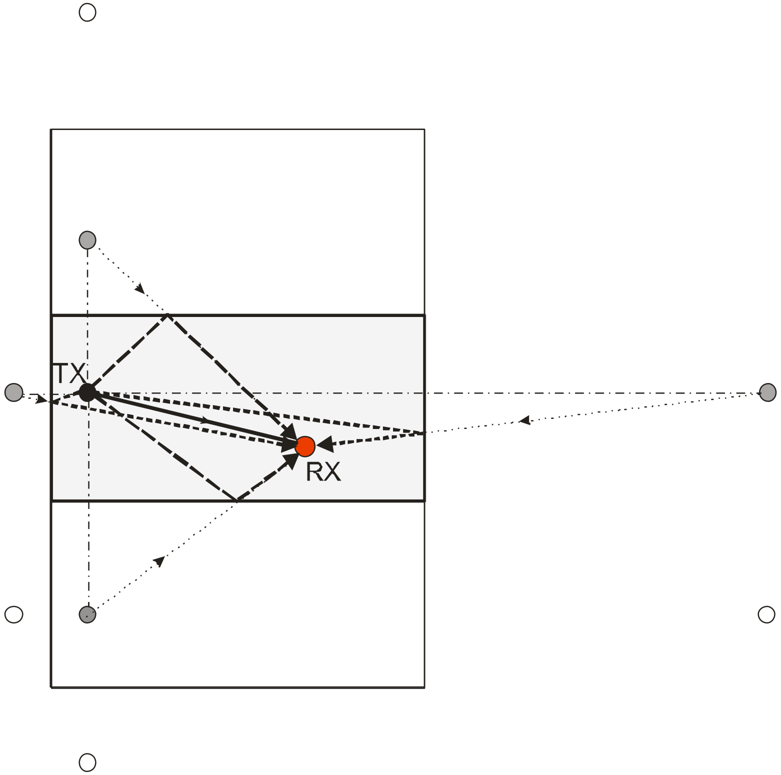
Rays are followed until their energy is below a threshold or if they get in the vicinity of the receiver.



Ray tracing

- Determines rays that can go from one TX position to one RX position
  - Uses imagining principle
  - Similar to techniques known from computer science

- Then determine attenuation of all those possible paths



Geometry Based Models

- Geometry-based models use the theory of electromagnetic wave propagation (Maxwell equations) to characterize wireless channels.
- Solutions can be written as a sum of plane waves

$$h(t, f, \vec{x}, \vec{y}) = \sum_p \beta_p e^{2\pi j(\phi_p + \langle \vec{\zeta}_p, \vec{x} \rangle - \langle \vec{\xi}_p, \vec{y} \rangle - f\tau_p + t\omega_p)},$$

where

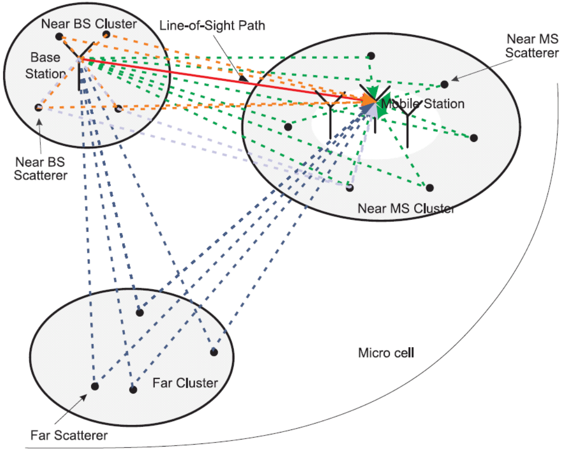
- β_p and ϕ_p are the amplitude and phase
- $\vec{\zeta}_p$ and $\vec{\xi}_p$ are the Tx and Rx wavevectors
- τ_p and ω_p are the delay and the Doppler shift

of path p.

Geometry Based Stochasic Models (GSCM)

- GSCM model the environment by placing clusters of scatterers in space
- Distribution of clusters and scatterers within clusters modeled stochstically
- Amplitude and phases of scatterers are modeled stochastically
- Use simplified ray tracing to rest of the path parameters
- Single bounce or multiple bounce

Geometry Based Stochasic Models (GSCM)



Geometry Based Stochasic Models (GSCM)

Advantages of GSCM

- Simpler than fully deterministic models
- More realistic than stochastic models
- Implicitly models mobility, MIMO, multi-user, etc
- Valid for regions

Disadvantages of GSCM

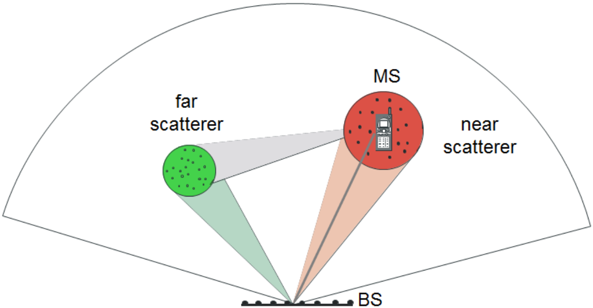
- Very hard to parameterize
- Can still be computationally expensive

Geometry Based Stochasic Models (GSCM)

- For every GSCM statistics can be computed
- Some GSCMs and stochastic models are equivalent
- Example: One ring model
  - Scatterers uniformly distributed on a ring around Rx
  - Equivalent to Rayleigh fading
- More sophisticated models (including MIMO)
  - COST 259 and 273
  - WINNER models
  - 3GPP spatial channel model

The COST 259 Approach

- Single-bounce model, no scatterers around BS
- Fixed relationship between AOD, AOA, and delay
- Well suited for smart antenna systems, but not MIMO

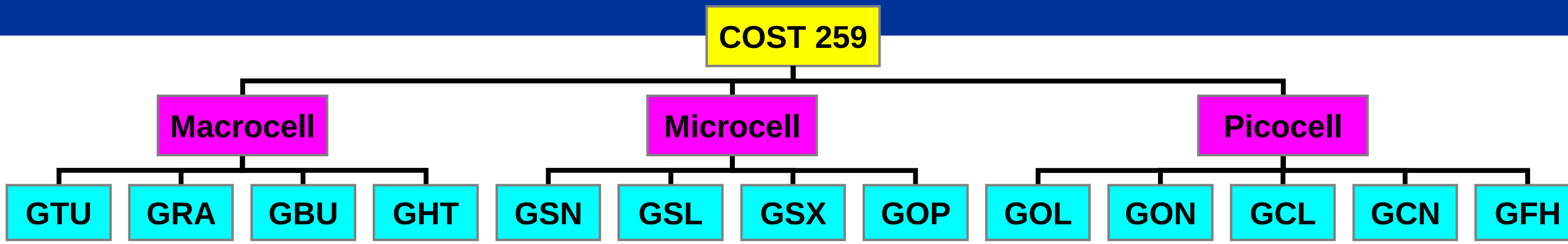


AOA: angle of arrival; AOD: angle of departure; BS/MS: base/mobile station

COST 259 DCM - Philosophy

- Parametric approach, WSSUS not required
- No statement about implementation method (stochastic or GSCM)
- Based on clustering approach
- Multi-layer approach:
  - Radio environments
  - Large-scale effects
  - Small-scale effects

Radio environments



GTU Generalized Typical Urban

GRA Generalized Rural Area

GBU Generalized Bad Urban

GHT Generalized Hilly Terrain

GSN Generalized Street NLOS

GSL Generalized Street Canyon LOS

GSX Generalized Street Crossing

GOP Generalized Open Place

GOL Generalized Office LOS

GON Generalized Office NLOS

GCL Generalized Corridor LOS

GCN Generalized Corridor NLOS

GFH Generalized Factory Hall

COST 259 DCM - Simulation procedure

Simulation steps:

1) select scenario

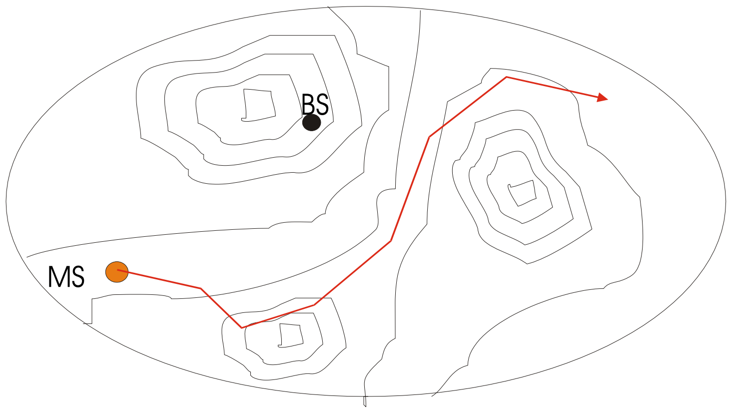
2) select global parameters (number of clusters, mean Rice factor,....)

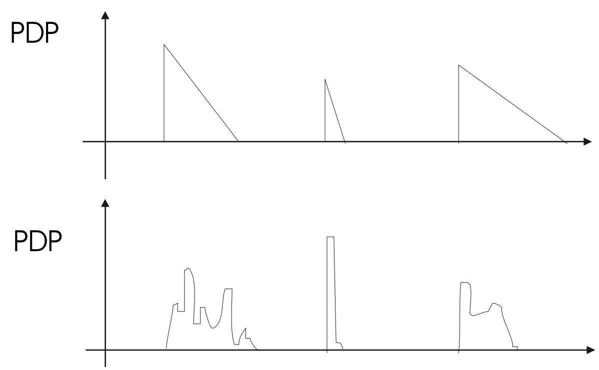
3) REPEAT

compute one realization of global parameters. This realization prescribes small-scale averaged power profiles (ADPS)

create many instantaneous complex impulse responses from this average ADPS

Generalized Hilly Terrain (GHT)





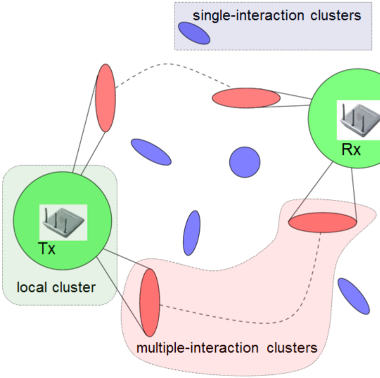
realization of
global parameters:
3 clusters, Rice factor of first: 3.2,
Rice factor of later clusters: 0
delay spread of clusters: 1,0.3,2s μ

COST 259 DCM - Important features

- Very realistic !
- Distinguishes 13 different radio environments
- Treats large-scale and small-scale variations
- Far scatterer clusters included, with birth/death process
- Delay spread and angular spread treated as (correlated) random variables
- Angular spectra are functions of delay
- Azimuth and elevation

The COST 273 Approach (1)

- Model based on clusters
- 3 different cluster types
- Clusters are placed geometrically and stochastically

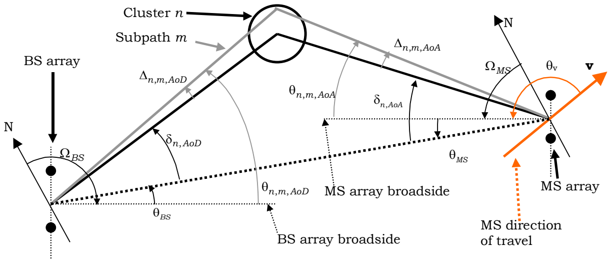


The COST 273 Approach (2)

- Local clusters around MS and/or BS may occur, depending on the scenario
- Any combination of delay and angles can be modelled, not limited to double scattering
- All parameters are given per cluster; there are no global spreads
- Direct coupling between AOAs and AODs; no “Kronecker” structure

The 3GPP Spatial Channel Mode (SCM)

- 3 different scenarios:
  - Suburban Macro,
  - Urban Macro,
  - Urban Micro
- Otherwise similar to COST 259
- Originally for 5MHz bandwidth, extensions to 100MHz exist



The IMT-Advanced Channel Model

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- Based on the outcomes of the WINNER project
- 13 different scenarios (also indoor)
- Introduces cross-correlation between large-scale parameters

Channel Simulation

- Sampled channels
- Correlation-based simulation
- Geometry based simulation

Sampling

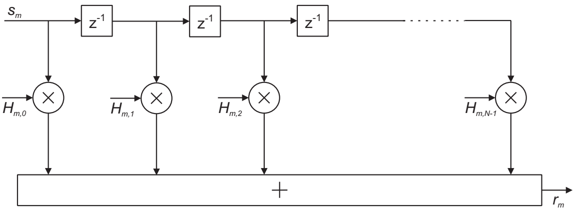
- Only sampled channels can be simulated (T_S is the sampling rate):

$$h[m,n] = h(mT_S, nT_S)$$

- Input-output relation

$$r[m] = \sum_{n=0}^{N-1} h[m,n]s[m-n] + n[m]$$

- Can be implemented as a tapped delay line



Sampling

- Special case: narrowband channel: $h[m, n] = 0$ for $n \neq 0$
- Special case: static channel $h[m, n] = h[n]$

Generation of correlated time series

- We wish to generate samples of a WSS process $h[m]$ with autocorrelation function (ACF)

$$R_h(m - m') = \mathcal{E}\{h[m]h^*[m']\}$$

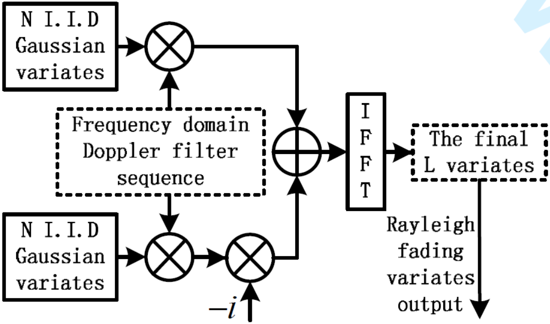
or equivalently with power spectrum desnity (PSD)

$$S_h(\nu) = \mathrm{DFT}\{R_h(\Delta m)\}$$

- Two main methods exist
  - Frequency-domain filtering
  - Time-domain filtering
  - Sum-of-sinusoids

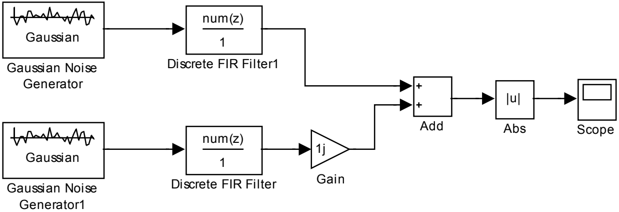
Frequency-domain filtering

- First generate N i.i.d. Gaussian random variates (real and imaginary)
- Shape them with a frequency domain filter corresponding to the desired PSD
- Apply an IFFT



Time-domain filtering

- First generate i.i.d. Gaussian random variates (real and imaginary)
- Pass them through a time-domain filter corresponding to the desired ACF
- Advantage: non-block based, no discontinuities



Problems

- The Doppler fading process is usually highly oversampled.
- Example: Sampling rate 7.68MHz, max. Doppler 500Hz
- For the frequency-domain method
  - $\Rightarrow$ Only a small part of the PSD is non-zero
  - $\Rightarrow$ large number of samples N required for accuracy
  - $\Rightarrow$ Large IFFT has high memory and complexity requirements
- For the time-domain method
  - $\Rightarrow$ A large number of filter coefficients required
  - $\Rightarrow$ High complexity
- Both methods can be improved by generating a correlated process with a lower sampling rate and then using interpolation

Generation of wideband impulse responses

- We wish to generate an US process $h[n]$, with a certain power delay profile (PDP = PSD)
- Same problem as before, but simpler since
  - Samples can be generated directly in the delay domain (n)
  - Process is sampled at lower rate
- However, interpolation might be necessary if the delays of taps are not multiples of the sampling rate

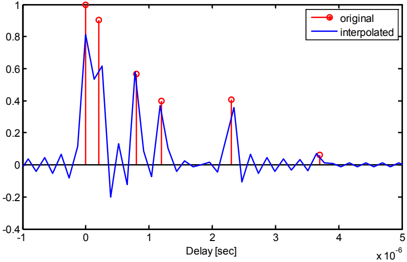
Example: sinc interpolation

- Impulse response

$$h(\tau) = \sum_{p=0}^{P-1} a_p \delta(\tau - \tau_p)$$

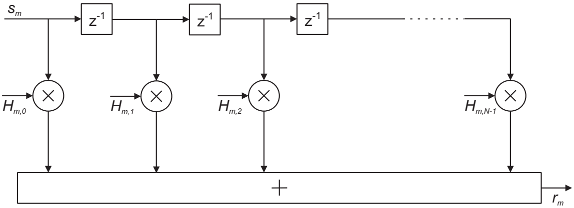
- Sampled at rate T_S:

$$h[n] = \sum_{p=0}^{P-1} a_p \, sinc(\tau - \frac{\tau_p}{T_S})$$



Generation of time-variant impulse responses

- Each tap of the tapped delay line is a time-correlated sequences multiplied with the weight of the tap



- Example: 3GPP channel model in Maltab

Stochastic MIMO models

- We wish to generate a MIMO channel $\mathbf{H}$ with a certain correlation matrix $\mathbf{R} = \mathcal{E}\left\{vec(\mathbf{H})\, vec(\mathbf{H})^H\right\}$
- Since the number of correlated samples is finite and small, we can use the direct method
- Let $\mathbf{R}^{\frac{1}{2}}$ be the matrix square root of $\mathbf{R}$ (can be computed with the Cholesky factorization) and $\mathbf{G}$ a matrix of i.i.d. Gaussian random variates. Then
$$\mathbf{H} = unvec\left(\mathbf{R}^{\frac{1}{2}}\, vec(\mathbf{G})\right)$$

Stochastic MIMO models (2)

Simplified MIMO models

- Weichselberger model

$$\mathbf{H} = \mathbf{U}_{Rx}(\mathbf{\Omega} \odot \mathbf{G})\mathbf{U}_{Tx}^{T}$$

- Kronecker model

$$\mathbf{H} = \mathbf{R}_{Rx}^{\frac{1}{2}}\mathbf{G}(\mathbf{R}_{Tx}^{\frac{1}{2}})^{T}$$

- i.i.d. model

$$\mathbf{H} = \mathbf{G}$$

Geometry based simulation

- Based on and used for geometry based model

$$h(t, f, \vec{x}, \vec{y}) = \sum_p \beta_p e^{2\pi j(\phi_p + \langle \vec{\zeta}_p, \vec{x} \rangle - \langle \vec{\xi}_p, \vec{y} \rangle - f\tau_p + t\omega_p)},$$

- Parameters for each path are either taken from a random distribution or from geometrical calculations
- In general more realistic (especially for MIMO) but also the most computationally complex

Example: Generation of time-correlated series using geometry based simulation

- For a narrowband SISO channel

$$h_m = \sum_p \beta_p e^{2\pi j(\phi_p + m\nu_p)},$$

where $\nu_p = \omega_p T_S$ is the normalized Doppler shift of path p

- If
  - $\beta_p = 1/\sqrt{P}$,
  - $\nu_p = \nu_{\max} \cos \psi_p$ where $\nu_{\max}$ is the maximum Doppler shift and ψ_p is the AoA of path p
  - ϕ_p and ψ_p are mutually independent and uniformly distributed in $[-\pi, \pi)$
- Then, as $P \to \infty$, the spectrum of h_m approaches

$$S_h(\nu) = \frac{1}{\pi\nu_{\max}\sqrt{1 - \left(\frac{\nu}{\nu_{\max}}\right)^2}}$$