# Modeling and Measurements for UWB Indoor MIMO Channels

Richard Prüller

Internal Workshop 5G and IoT
September 8, 2021

TECHNISCHE UNIVERSITÄT WIEN

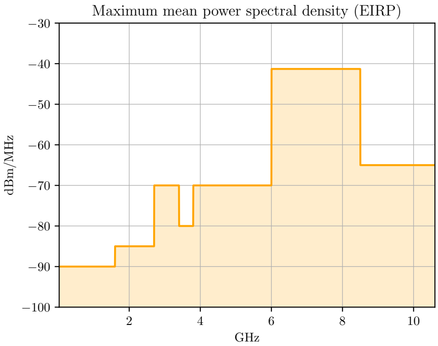
institute of telecommunications

# Outline

# Motivation

# Ultra wideband channels

- Indoor and short range communication
- High datarates and reliability
- Already regulated

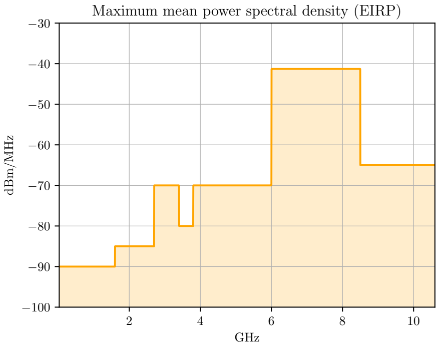



ETSI EN 302 065-1 V2.1.1 (2016-11)

# Ultra wideband channels

- Indoor and short range communication
- High datarates and reliability
- Already regulated

- Frequency-selective
- Antennas are part of the channel



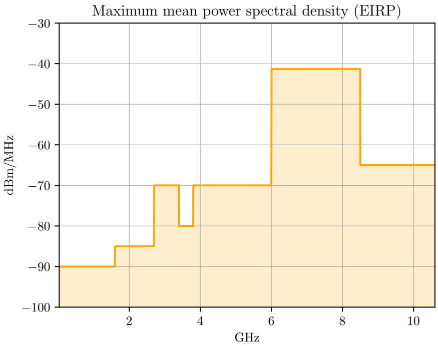

ETSI EN 302 065-1 V2.1.1 (2016-11)

# Ultra wideband channels

- Indoor and short range communication
- High datarates and reliability
- Already regulated

- Frequency-selective
- Antennas are part of the channel

- Combination with MIMO is very interesting
- Channel statistics largely unknown

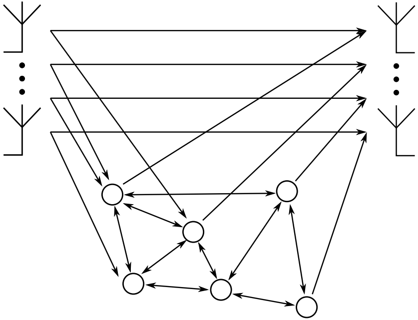



ETSI EN 302 065-1 V2.1.1 (2016-11)

# Propagation graphs

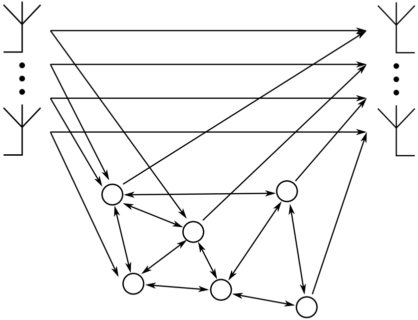
# Propagation graphs

- MIMO channel model
- Based on scatterers
- Frequency-selective
- Spatially consistent
- Transfer function includes up to infinite scattering bounces



# Propagation graphs

- MIMO channel model
- Based on scatterers
- Frequency-selective
- Spatially consistent
- Transfer function includes up to infinite scattering bounces
- **Channel PDF and most statistics unknown**



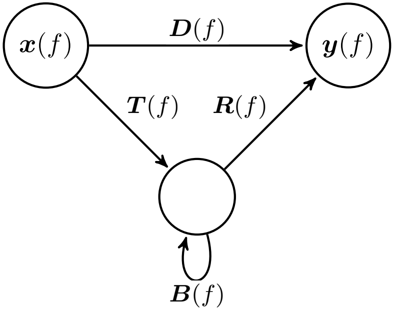
# Propagation graphs[1]

Frequency-selective MIMO channel

$$\boldsymbol{y}(f) = \boldsymbol{H}(f)\boldsymbol{x}(f).$$

The graph visualizes the channel

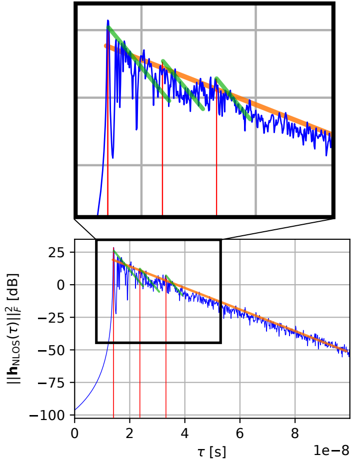
$$\boldsymbol{H}(f) = \boldsymbol{D}(f) + \boldsymbol{R}(f)\left(\sum_{k=0}^{\infty} \boldsymbol{B}^k(f)\right)\boldsymbol{T}(f)$$
$$= \underbrace{\boldsymbol{D}(f)}_{\boldsymbol{H}_{\mathrm{LOS}}(f)} + \underbrace{\boldsymbol{R}(f)(\boldsymbol{I} - \boldsymbol{B}(f))^{-1}\boldsymbol{T}(f)}_{\boldsymbol{H}_{\mathrm{NLOS}}(f)}$$




[1] T. Pedersen, G. Steinböck, and B. H. Fleury, “Modeling of Reverberant Radio Channels Using Propagation Graphs,” IEEE Trans. Antennas Propagat., vol. 60, no. 12, pp. 5978–5988, Dec. 2012

# Parametrization - Goals and Assumptions

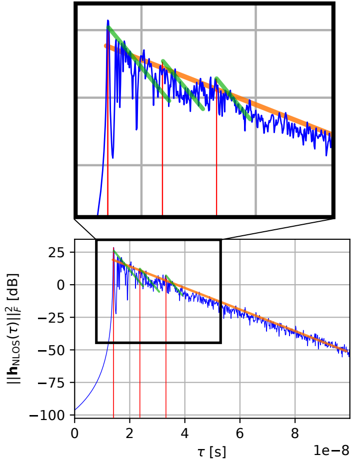
- Simplification with regard to statistical treatment
- Doubly exponential decay similar to the Saleh-Valenzuela model[2]
- Express internal parameters in terms of:
  - $\rho_1$, overall exponential (cluster) decay rate in dB/s
  - $\rho_2$, exp. decay rate within cluster (ray decay rate) in dB/s
  - $K$-factor




[2] A. A. M. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," IEEE Journal on Selected Areas in Communications, vol. 5, no. 2, pp. 128–137, Feb. 1987

# Parametrization - Goals and Assumptions

- Simplification with regard to statistical treatment
- Doubly exponential decay similar to the Saleh-Valenzuela model[2]
- Express internal parameters in terms of:
  - $\rho_1$, overall exponential (cluster) decay rate in dB/s
  - $\rho_2$, exp. decay rate within cluster (ray decay rate) in dB/s
  - $K$-factor
- Scatterers are i.i.d.
- Omnidirectional antennas
- Antennas at Tx/Rx are close to each other
- $\sqrt{\mathrm{Var}\{\tau\}} f_{\min} \gg 1$




[2] A. A. M. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," IEEE Journal on Selected Areas in Communications, vol. 5, no. 2, pp. 128–137, Feb. 1987

# Parametrization

$$\boldsymbol{H}(f) = \boldsymbol{D}(f) + \boldsymbol{R}(f) \underbrace{\left( \sum_{k=0}^{\infty} \boldsymbol{B}^k(f) \right)}_{\boldsymbol{S}(f)} \boldsymbol{T}(f)$$

$$D_{mn}(f) = \frac{\varepsilon_D}{4\pi\tau_{D,mn} f} e^{-j2\pi\tau_{D,mn} f}$$

$$T_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{T,mn}\gamma} e^{-j2\pi\tau_{T,mn} f + j\phi_{T,n}}$$

$$R_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{R,mn}\gamma} e^{-j2\pi\tau_{R,mn} f + j\phi_{R,m}}$$

$$B_{mn}(f) = (1 - \delta_{mn})\beta e^{-j2\pi\tau_{B,mn} f}$$

# Parametrization

$$\boldsymbol{H}(f) = \boldsymbol{D}(f) + \boldsymbol{R}(f) \underbrace{\left(\sum_{k=0}^{\infty} \boldsymbol{B}^k(f)\right)}_{\boldsymbol{S}(f)} \boldsymbol{T}(f)$$

- Cluster power decays with $\approx (N_\mathrm{S} - 1)\beta^2 / \mathrm{E}\{\tau_B\}$
- Exponential decay in $\boldsymbol{R}(f)$ and $\boldsymbol{T}(f)$
- Random phase shifts per Tx/Rx and scatterer
- Internal parameters are $\alpha$, $\beta$ and $\gamma$

$$D_{mn}(f) = \frac{\varepsilon_D}{4\pi\tau_{D,mn} f} e^{-j2\pi\tau_{D,mn} f}$$

$$T_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{T,mn}\gamma} e^{-j2\pi\tau_{T,mn} f + j\phi_{T,n}}$$

$$R_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{R,mn}\gamma} e^{-j2\pi\tau_{R,mn} f + j\phi_{R,m}}$$

$$B_{mn}(f) = (1 - \delta_{mn})\beta e^{-j2\pi\tau_{B,mn} f}$$

# Computing $\alpha$, $\beta$ and $\gamma$

$$K := \frac{P_{\mathrm{LOS}}}{P_{\mathrm{NLOS}}} := \frac{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \| \boldsymbol{H}_{\mathrm{LOS}}(f) \|_{\mathrm{F}}^2 \right\} df}{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \| \boldsymbol{H}_{\mathrm{NLOS}}(f) \|_{\mathrm{F}}^2 \right\} df}$$

# Computing $\alpha$, $\beta$ and $\gamma$

$$K := \frac{P_{\mathrm{LOS}}}{P_{\mathrm{NLOS}}} := \frac{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \|\boldsymbol{H}_{\mathrm{LOS}}(f)\|_{\mathrm{F}}^2 \right\} df}{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \|\boldsymbol{H}_{\mathrm{NLOS}}(f)\|_{\mathrm{F}}^2 \right\} df}$$

$$P_{\mathrm{LOS}} = \frac{\varepsilon_D (f_{\max} - f_{\min})}{(4\pi)^2 f_{\max} f_{\min}} \sum_{m=1}^{N_{\mathrm{R}}} \sum_{n=1}^{N_{\mathrm{T}}} \frac{1}{\tau_{D,mn}^2}$$

# Computing $\alpha$, $\beta$ and $\gamma$

$$K := \frac{P_{\mathrm{LOS}}}{P_{\mathrm{NLOS}}} := \frac{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \|\boldsymbol{H}_{\mathrm{LOS}}(f)\|_{\mathrm{F}}^2 \right\} df}{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{ \|\boldsymbol{H}_{\mathrm{NLOS}}(f)\|_{\mathrm{F}}^2 \right\} df}$$

$$P_{\mathrm{LOS}} = \frac{\varepsilon_D (f_{\max} - f_{\min})}{(4\pi)^2 f_{\max} f_{\min}} \sum_{m=1}^{N_{\mathrm{R}}} \sum_{n=1}^{N_{\mathrm{T}}} \frac{1}{\tau_{D,mn}^2}$$

$$P_{\mathrm{NLOS}} \approx \frac{\alpha^2 N_{\mathrm{R}} N_{\mathrm{T}} N_{\mathrm{S}} (f_{\max} - f_{\min})}{f_{\min} f_{\max}} Q(\beta, \gamma)$$

$$Q(\beta,\gamma) = \frac{1}{1 - (N_{\mathrm{S}} - 1)\beta^2} \left( M_{\tau_R + \tau_T}(2\gamma) + \frac{(N_{\mathrm{S}} - 1)\beta^2}{1 + \beta^2} \left( M_{\tau_R}(2\gamma) M_{\tau_T}(2\gamma) - M_{\tau_R + \tau_T}(2\gamma) \right) \right)$$

# Computing $\alpha$, $\beta$ and $\gamma$

$$K := \frac{P_{\mathrm{LOS}}}{P_{\mathrm{NLOS}}} := \frac{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{\|\boldsymbol{H}_{\mathrm{LOS}}(f)\|_{\mathrm{F}}^2\right\} df}{\int_{f_{\min}}^{f_{\max}} \mathrm{E}\left\{\|\boldsymbol{H}_{\mathrm{NLOS}}(f)\|_{\mathrm{F}}^2\right\} df}$$

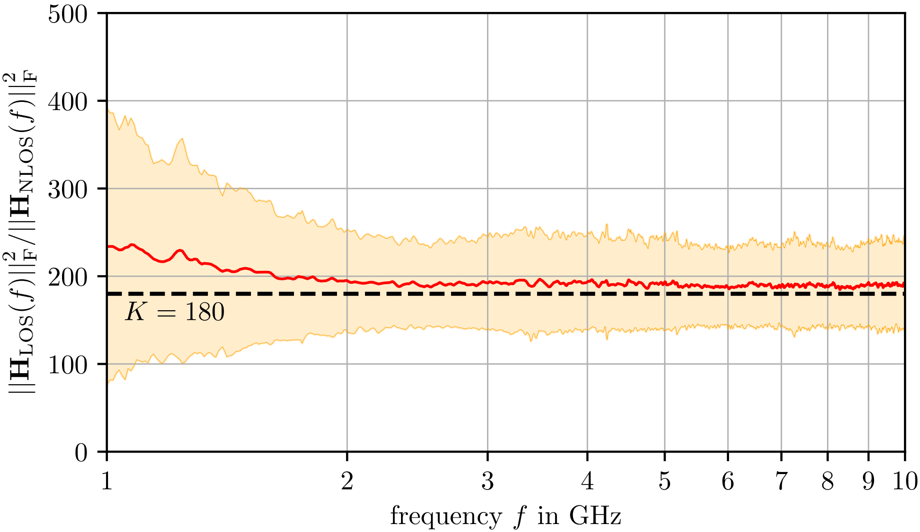
$$P_{\mathrm{LOS}} = \frac{\varepsilon_D (f_{\max} - f_{\min})}{(4\pi)^2 f_{\max} f_{\min}} \sum_{m=1}^{N_{\mathrm{R}}} \sum_{n=1}^{N_{\mathrm{T}}} \frac{1}{\tau_{D,mn}^2}$$

$$P_{\mathrm{NLOS}} \approx \frac{\alpha^2 N_{\mathrm{R}} N_{\mathrm{T}} N_{\mathrm{S}} (f_{\max} - f_{\min})}{f_{\min} f_{\max}} Q(\beta, \gamma)$$

$$Q(\beta,\gamma) = \frac{1}{1-(N_{\mathrm{S}}-1)\beta^2}\left(M_{\tau_R+\tau_T}(2\gamma) + \frac{(N_{\mathrm{S}}-1)\beta^2}{1+\beta^2}\Big(M_{\tau_R}(2\gamma)M_{\tau_T}(2\gamma) - M_{\tau_R+\tau_T}(2\gamma)\Big)\right)$$

$$\gamma = \frac{\rho_2}{10\log e} \qquad \beta \approx \sqrt{\frac{1}{N_{\mathrm{S}}-1}10^{\frac{\mathrm{E}\{\tau_B\}\rho_1}{10}}} \qquad \alpha \approx \sqrt{\frac{\varepsilon_D \sum_{m=1}^{N_{\mathrm{R}}} \sum_{n=1}^{N_{\mathrm{T}}} \tau_{D,mn}^{-2}}{(4\pi)^2 K N_{\mathrm{R}} N_{\mathrm{T}} N_{\mathrm{S}} Q(\beta,\gamma)}}$$

# Verification of the approximation



# Model tuning

Motivation

Propagation graphs

Model tuning

Measurement setup

Measurement results

Conclusion

# Random phases

$$\boldsymbol{H}(f) = \underbrace{\boldsymbol{D}(f)}_{\boldsymbol{H}_{\text{LOS}}(f)} + \underbrace{\boldsymbol{R}(f)(\boldsymbol{I} - \boldsymbol{B}(f))^{-1}\boldsymbol{T}(f)}_{\boldsymbol{H}_{\text{NLOS}}(f)}$$

$$D_{mn}(f) = \frac{\varepsilon_D}{4\pi\tau_{D,mn}f} e^{-j2\pi\tau_{D,mn}f}$$

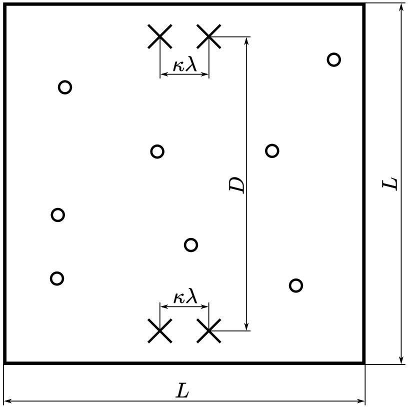
$$T_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{T,mn}\gamma} e^{-j2\pi\tau_{T,mn}f + j\phi_{T,mn}}$$

$$R_{mn}(f) = \sqrt{\frac{\alpha}{f}} e^{\tau_{R,mn}\gamma} e^{-j2\pi\tau_{R,mn}f + j\phi_{R,mn}}$$

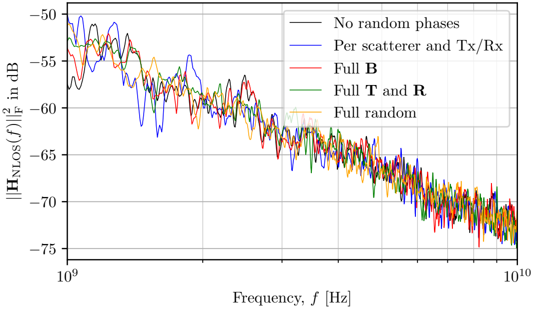
$$B_{mn}(f) = (1 - \delta_{mn})\beta e^{-j2\pi\tau_{B,mn}f + j\phi_{B,mn}}$$

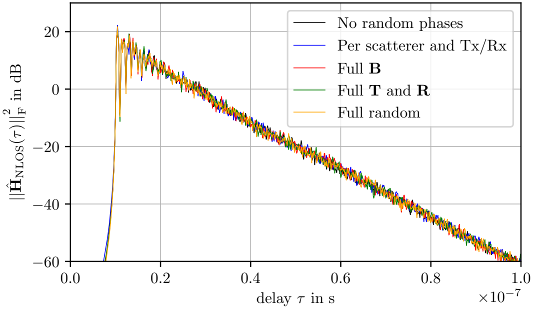
# Simulation setup

| Parameter | Symbol | Value |
|---|---|---|
| Tx and Rx | | 2 by 2 quadratic arrays |
| Antennas | | omnidirectional |
| Antenna spacing | | $\kappa_0 c_0 / f_0$ |
| Antenna spacing factor | $\kappa_0$ | 1 |
| Frequency | $f_0$ | 5 GHz |
| Tx – Rx distance | $D_0$ | 3 m |
| Number of scatterers | $N_S$ | 100 |
| Scatterer box size | $L_0$ | 5 m |
| Minimum scatterer distance | | 1.5 m |
| Cluster decay rate | $\rho_1$ | $-1$ dB/ns |
| Ray decay rate | $\rho_2$ | $-2$ dB/ns |
| $K$-factor | $K$ | 180 |
| Realizations | $M$ | 1000 |

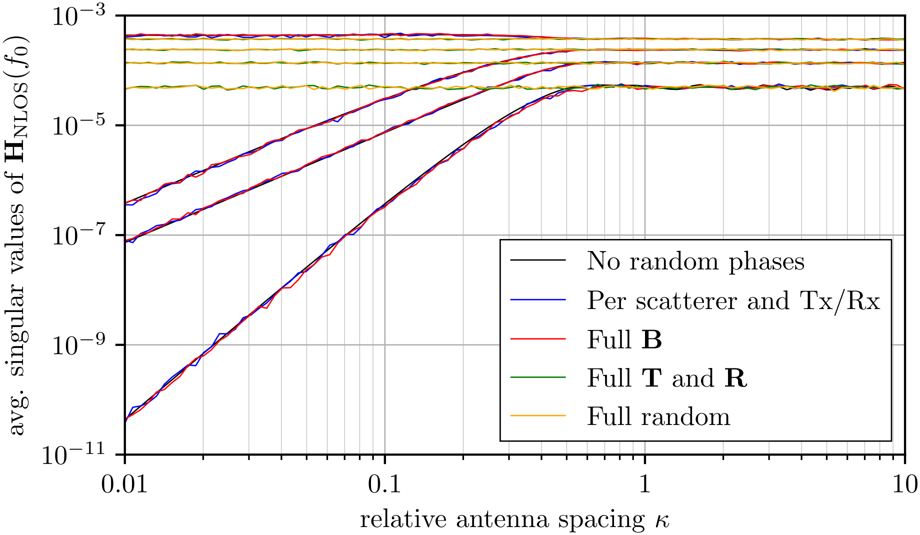


# Realizations - Different phase choices



# Singular values - Different phase choices

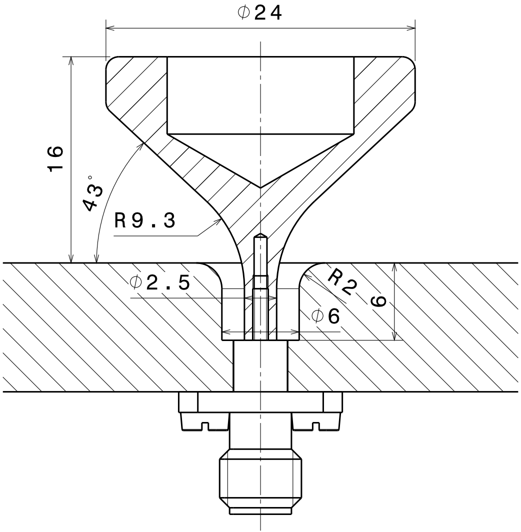


# Measurement setup

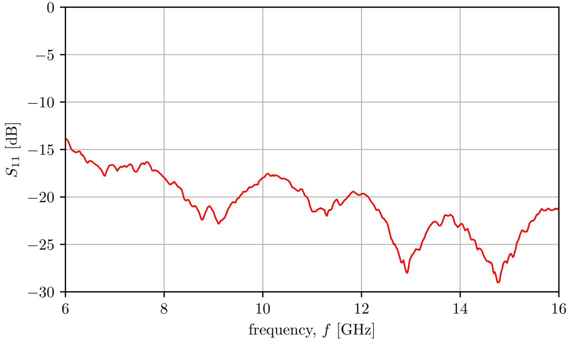
# Key measurement characteristics

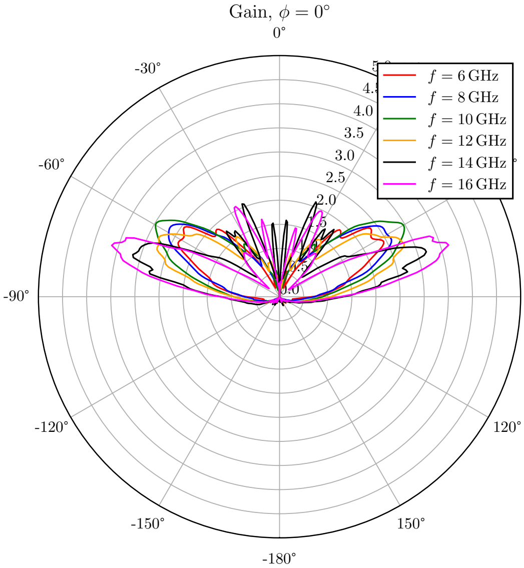
- 4x4 MIMO channels realized with virtual ULAs
- VNA measurement from 6GHz to 10GHz
- Varying distances between antennas within arrays

# UWB antenna design



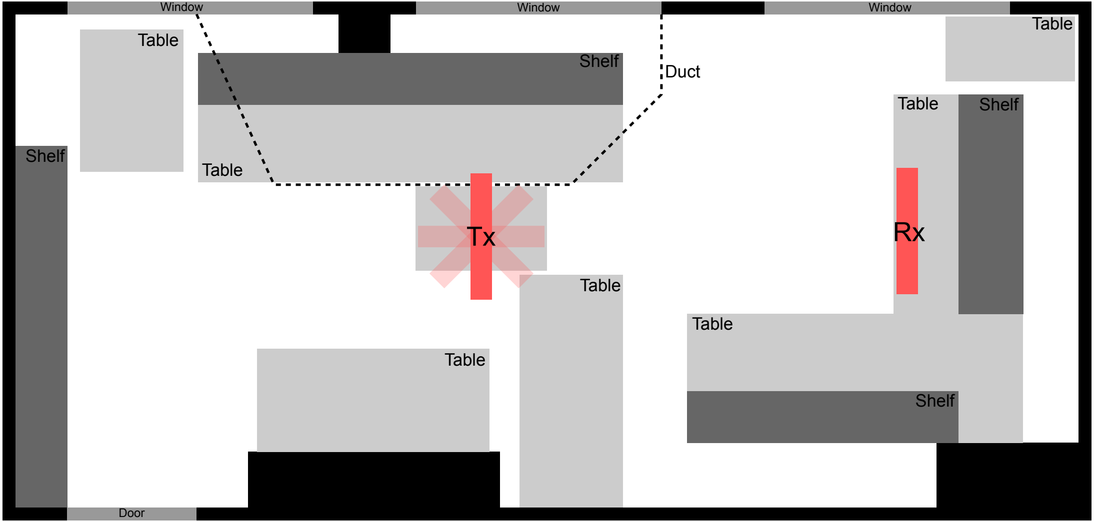

# UWB antenna characteristics



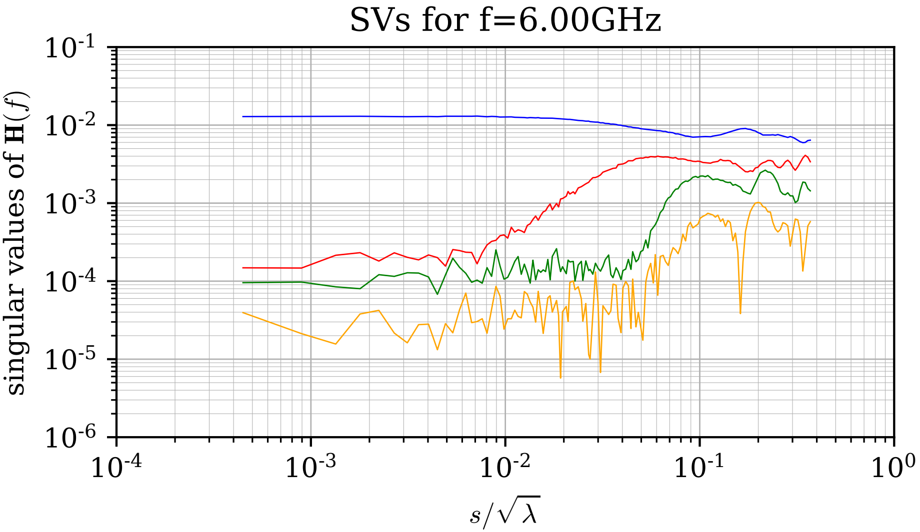
# Measurement location

# Measurement location

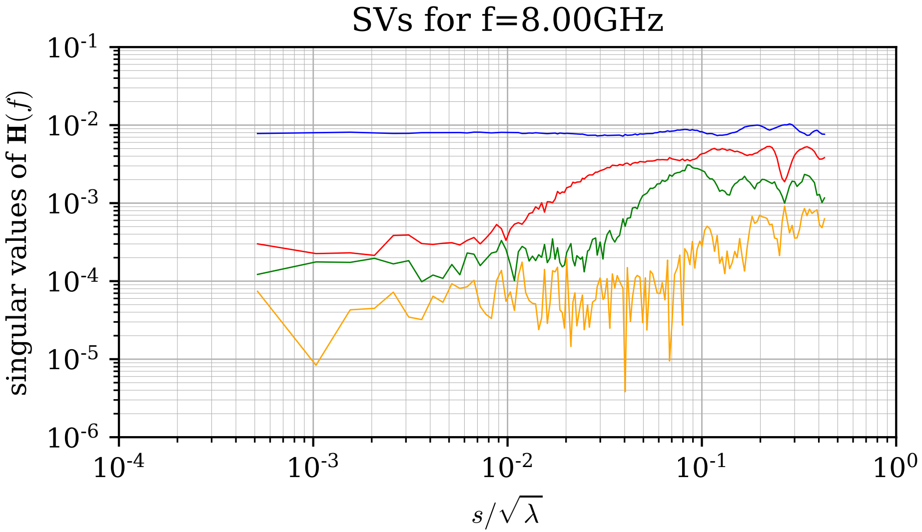


# Measurement results

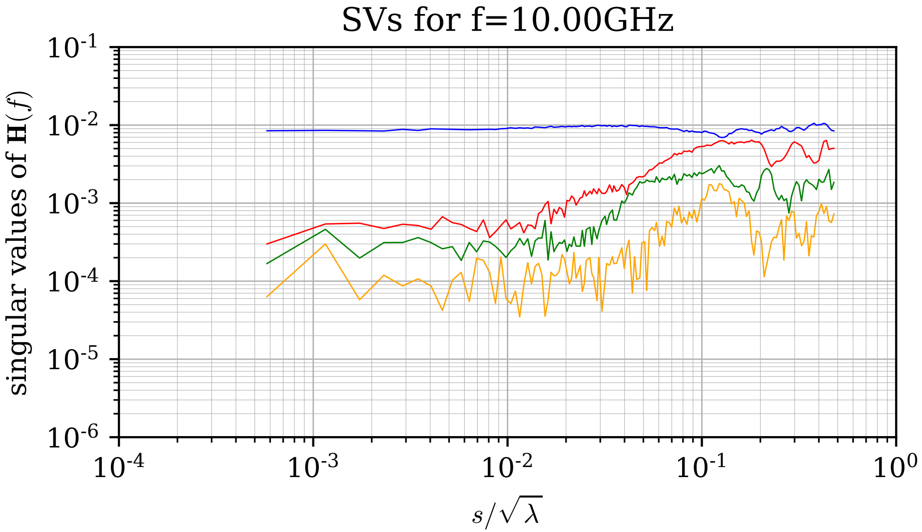
# SVs over array spacing



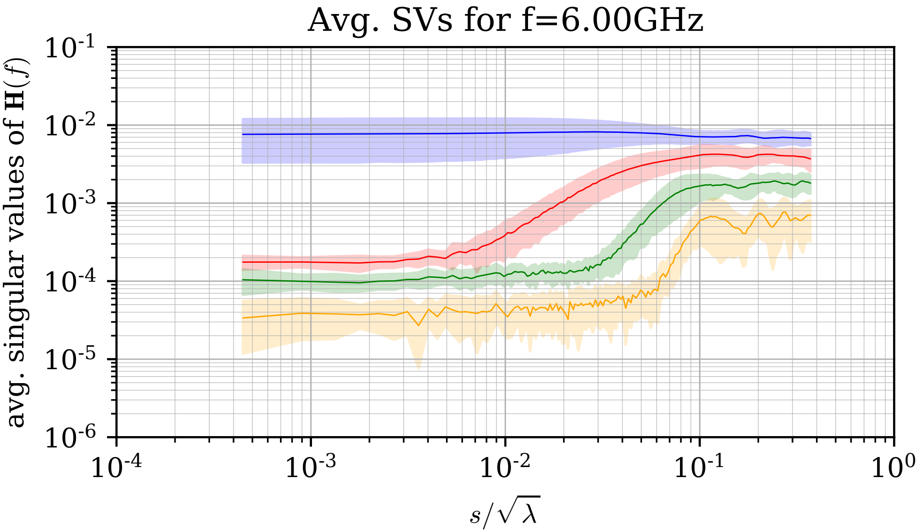
# SVs over array spacing



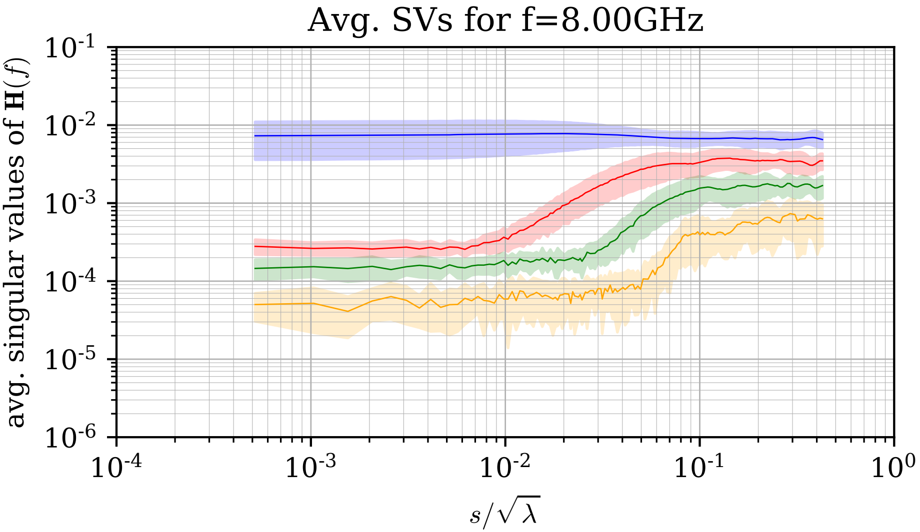
# SVs over array spacing



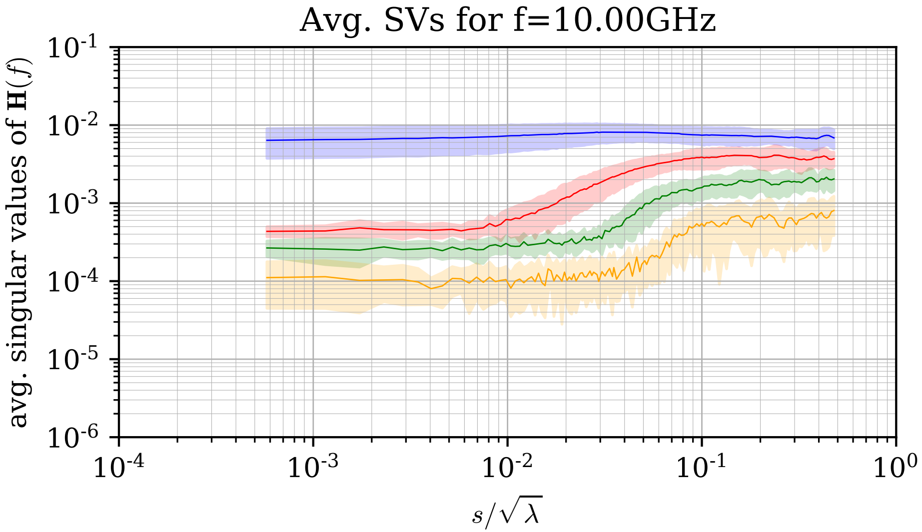
# SVs over array spacing, all measurements



# SVs over array spacing, all measurements



# SVs over array spacing, all measurements



# Conclusion

# Conclusion

- Propagation graphs are an efficient simulation model for UWB MIMO channels
- Care must be taken when parametrizing them
- A UWB measurement setup campaign was conducted
- Measurement results show similar behavior as simulations

Thank you for your attention!

TECHNISCHE UNIVERSITÄT WIEN

institute of telecommunications