XXII RiNEm

Statistical methods for joint antenna-radio channel modelling

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Outline

- **Introduction – motivation**
  - Problem, complexity, benefits
- **Propagation-antenna composite channel**
  - Handset
  - Laptop
  - Access point
  - UWB RFID
  - Textile antenna for WBAN
  - MIMO terminal
- **Modeling of exposure to EM waves**
  - Uplink
  - downlink
- **Conclusion**

Introduction - motivation

- **Stochastic aspects in EM**
  - Far from new!
  - But still not so common…
  - Antennas are deterministic, aren't they ?

- **Contributions from URSI-France commissions**
  - B, C: antennas & radio channels
  - E: EMC, reverberation chambers
  - K: dosimetry

Introduction - motivation

➔ **Antennas & channels (jointly or separately)**

Radio link characteristics

- Depend on a large number of parameters
- Exhibit a large degree of variability according to use cases
- Are in part controlled by deterministic elements (e.g. transceivers) and in part impacted by random contributors (e.g. propagation channel, device environment)

Questions

- How to model deterministic and random aspects jointly ?
- What benefits can be expected ?

Introduction - motivation

- **Fundamental remarks**
  - Nearly all phenomena are deterministic (except for quantum effects, noise…)
  - The frontier between deterministic and stochastic refer to our incomplete knowledge. This particularly addresses:
    - The propagation environment (buildings, furniture…)
    - The local environment around the devices (near field or so)
    - The detailed characteristics of the devices (by far imperfectly known in the frequency, angular, spatial.. domains)

➔ electromagnetism, like other areas of physis lends itself to stochastic modeling (although not so commonly practiced)

Introduction - motivation

- **Deterministic vs. stochastic models**
  - transceivers
    - Can be modelled deterministically through advanced EM tools

      BUT
    - Very complicated designs, hard to describe accurately, hard to simulate accurately (cf. low vs. high frequencies)
  - Near field (close) environment
    - Ditto: can be modelled deterministically but in practice hardly so

      AND
    - Highly variable according to use cases
  - Propagation environment (far field or so)
    - Ditto: can be modelled deterministically (e.g. ray tracing) but inaccurately

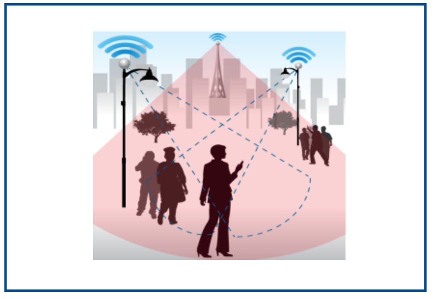
      AND
    - Highly variable according to use cases – not feasible to model deterministically all possible propagation environments
  - uncertainties similarly apply to measurements (owing to inaccuracies, too large number of parameters to measure…)

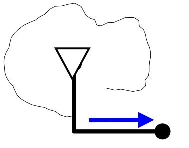
Introduction - motivation

- **Fundamental complexity**
  - Stochastic input-output relation

PDF(I_1,I_2,I_3,…)

(correlated multivariate)

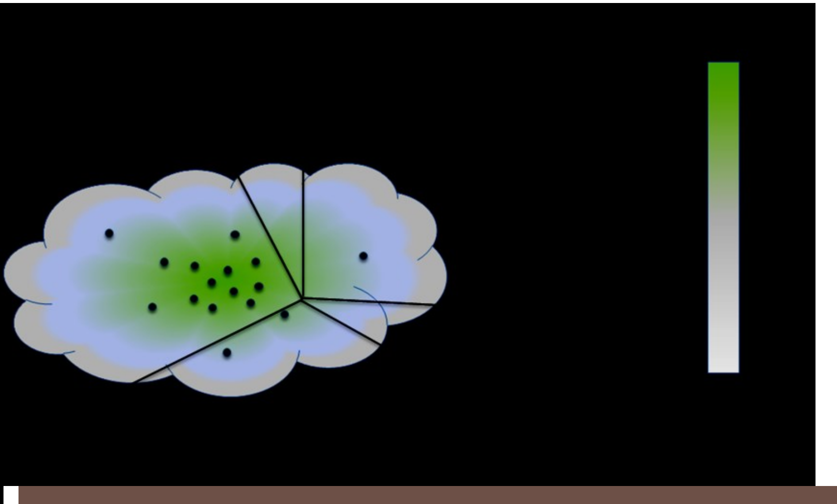




PDF(O_1,O_2,O_3,…)

(correlated multivariate)

  - Dimensionality curse



Introduction - motivation

- **Fundamental complexity**
  - Mitigation
    - Reduce the stochastic space to a reduced “typical” subspace, resort to a limited set of input (and output) parameters
    - Be happy with a sparse sampling of the stochastic space
    - Approximate the input-output relation (surrogate modeling)
    - Polynomial chaos expansion
    - Deal with sources of randomness sequentially, not all together
    - …

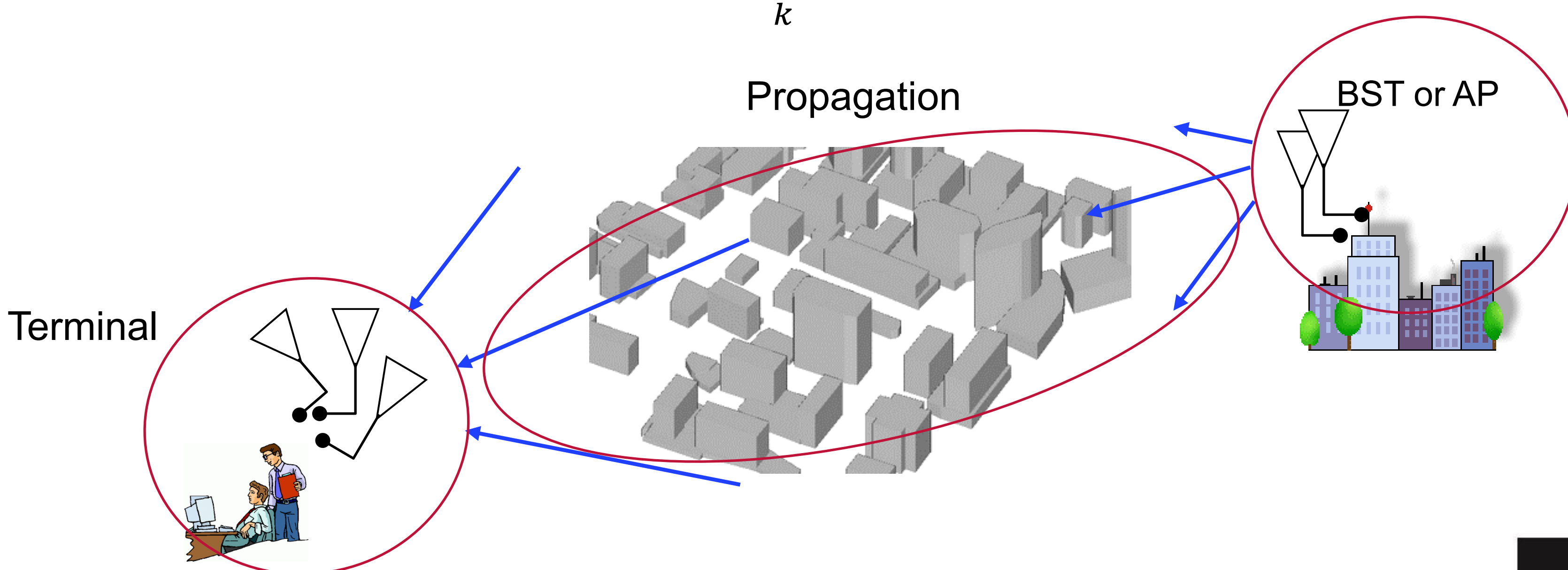
Introduction - motivation

- **Benefits – application needs (some examples)**
  - Modeling of the composite propagation-antenna channel
    - Evaluate the performance of alternative physical layer schemes for wireless networks
    - Address the impact of real world use conditions on the true performance of devices (e.g wearables, RFID)
    - Better dimension network infrastructure from better understood real world performance (average, worst case)
  - Modeling of the exposure to electromagnetic waves
    - From devices worn by or close to humans
    - From ambient EM waves (distant sources)
    - Through statistical distributions allowing to estimate the risk of exceeding legal limits

Propagation-antenna composite channel

- **Approach**
  - Categorization (terminals, close environment, far field propagation environment, use cases…) yields the mixture

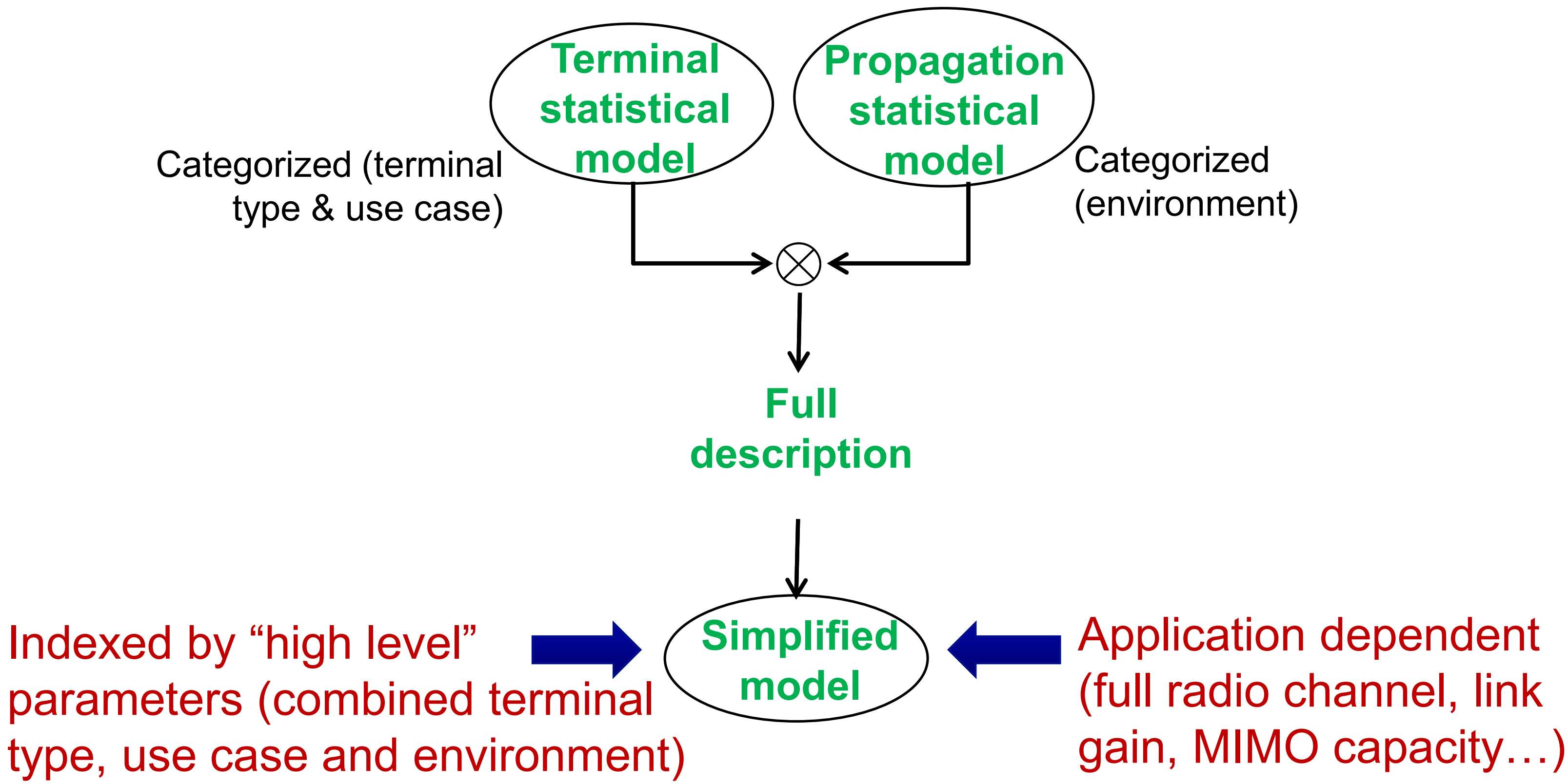
$$PDF(I) = \sum_{k} PDF(I/k)P_K(k)$$



Propagation-antenna composite channel

Approach

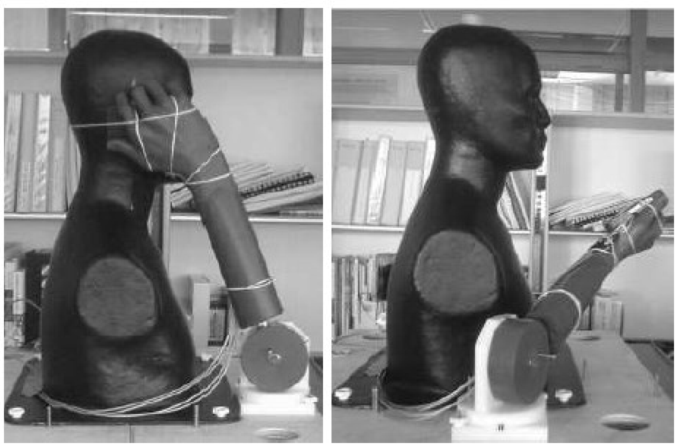
- « propagation aware » modeling

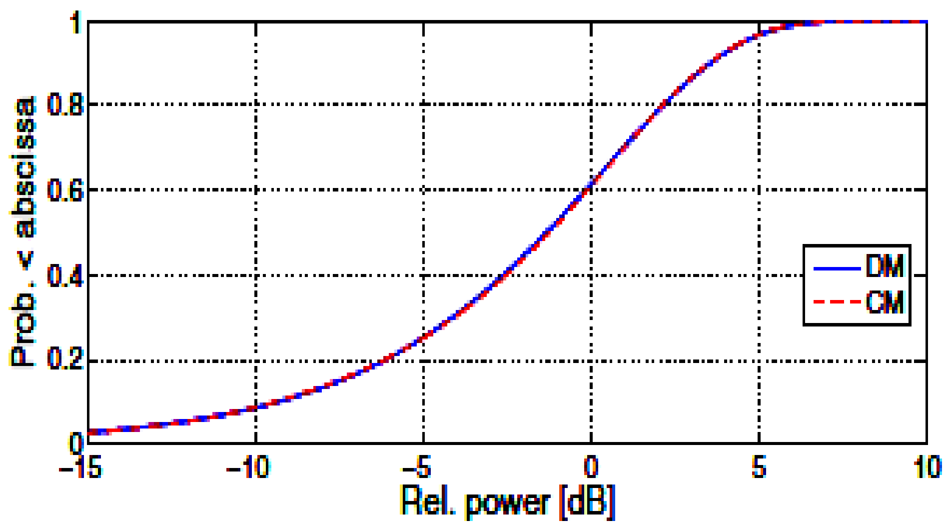


Propagation-antenna composite channel

Approach

- « propagation aware » modeling:
- why it works: “Composite channel” method : validation of the combination between (far field) propagation and antenna patterns including the immediate environment





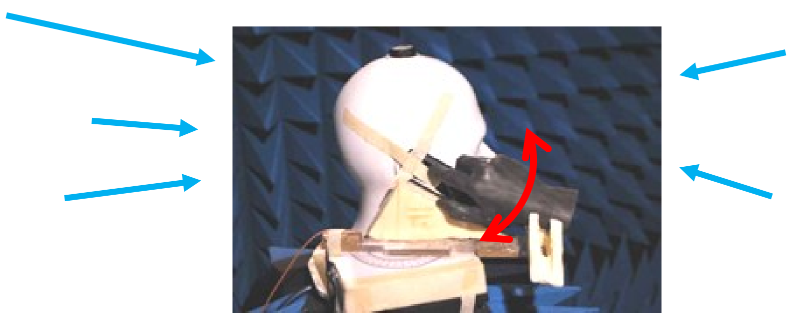
F. Harryson et al., “The Composite Channel Method: Efficient Experimental Evaluation of a Realistic MIMO Terminal in the Presence of a Human Body,” IEEE VTC Spring, 2008

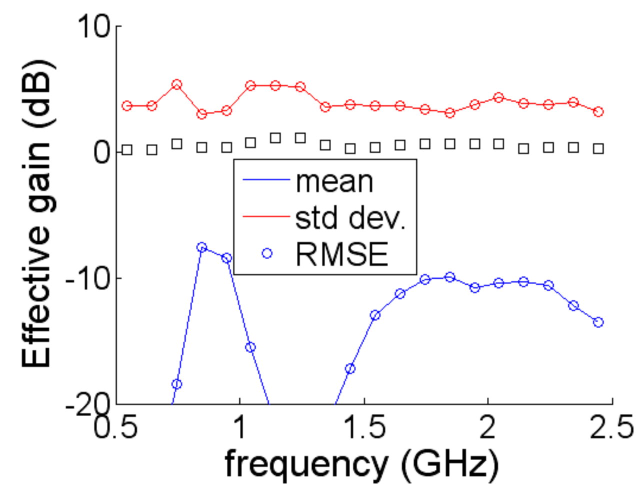
Propagation-antenna composite channel

Example: wireless terminal effective gain statistics

- Partial measurement of the antenna radiation pattern (2D in azimuth, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: phantom head, a few orientations/tilt of the handset in talk mode
- Model of the local multipath propagation channel (stochastic, e.g. extracted from standard propagation channel models)

➔ Lognormal distribution of the effective gain



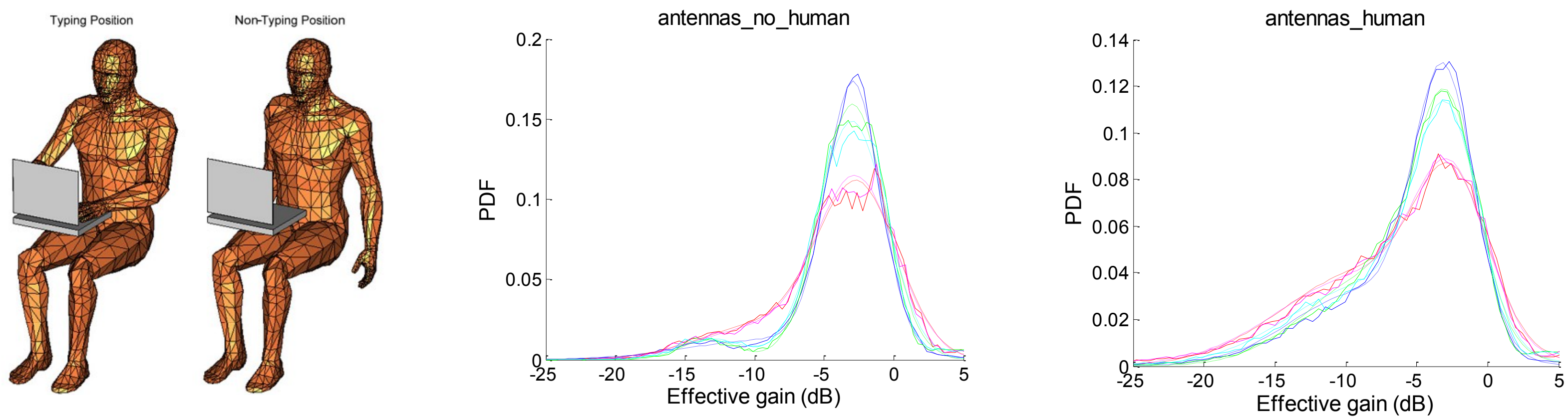


A. Sibille, “Statistical Modeling of the Radio-Electric Properties of Wireless Terminals in their Environment,” IEEE Antennas and Propagation Magazine, Vol. 54 , 6, 2012

Propagation-antenna composite channel

- **Example: wireless terminal effective gain statistics**
  - Full simulation of the antenna radiation pattern (3D, H & V polarizations)
  - Involvement of a « typical » close environment in a limited set of variable parameters: a human body in sitting position and differing arms configuration
  - Model of the local multipath propagation channel (stochastic, e.g. extracted from standard propagation channel models)

➔ Mixture of two distributions for the effective gain (laptop/body obstruction or not)



A. Sibille, J. Guterman, A. Moreira, and C. Peixeiro, "Performance evaluation of 2.4 GHz laptop antennas using a joint antenna-channel statistical model," COST 2100 TD-09-930, Vienna, Austria, 28-30 September 2009.

Propagation-antenna composite channel

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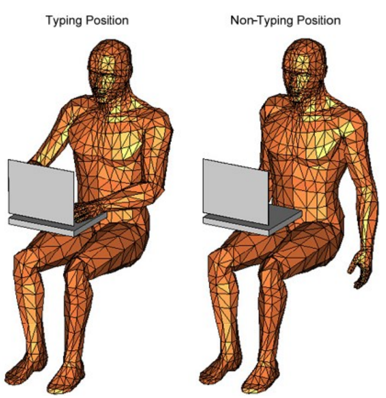

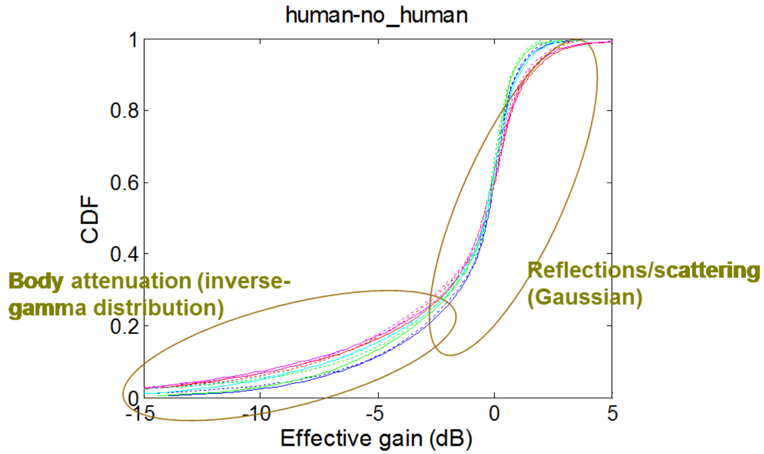

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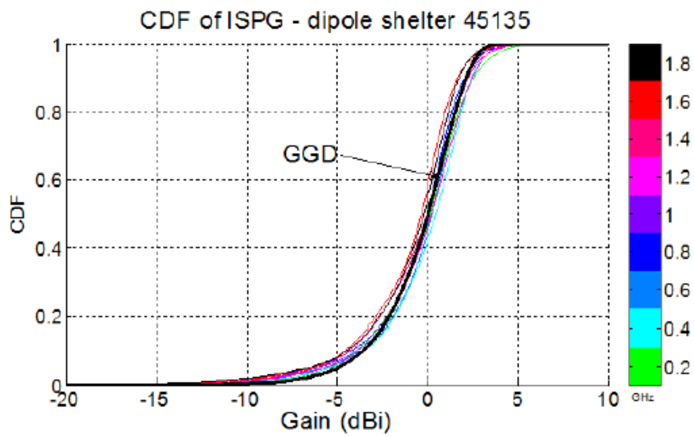
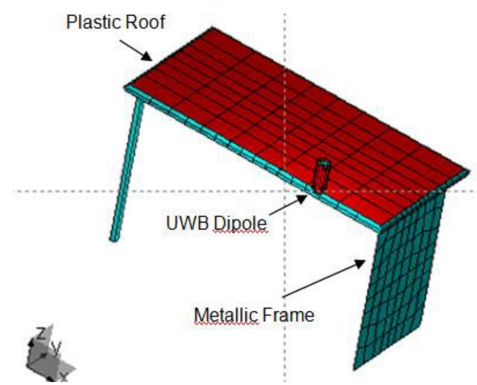
Propagation-antenna composite channel

Example: wireless terminal ISPG statistics

- Full simulation of the antenna radiation pattern (3D, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: urban furniture supporting an access point antenna
- ISPG = antenna realized gain in the nominal angular sector of the access point

➔ Slightly asymetrical distribution of the ISPG in log. scale (low gain tail)





X. Zeng et al., "Statistical Modeling of Antenna: Urban Equipment Interactions for LTE Access Points," International Journal of Antennas and Propagation, vol. 2012, Article ID 292018

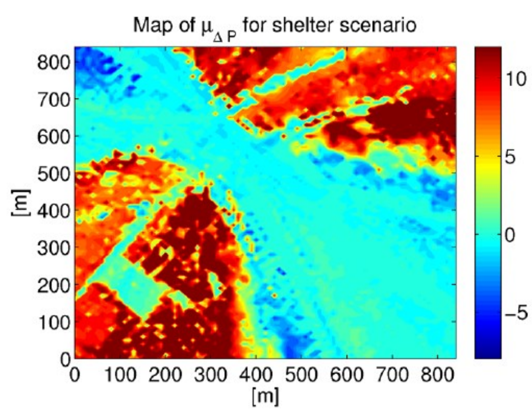
Propagation-antenna composite channel

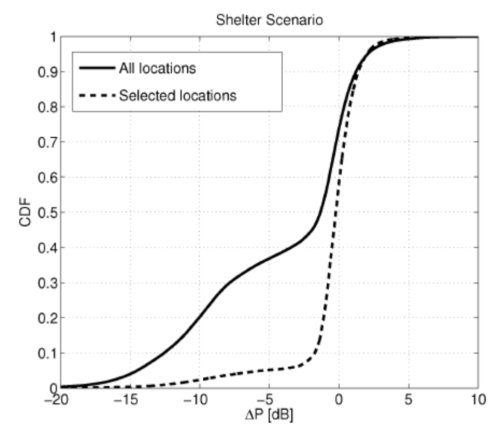
Example: channel path gain statistics

- Full simulation of the antenna radiation pattern (3D, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: urban furniture supporting an access point antenna
- ISPG = antenna realized gain in the nominal angular sector of the access point

➔ Slightly asymetrical distribution of the ISPG in log. scale (low gain tail)

➔ Resulting in an excess path loss tail in ray-tracing computed channels





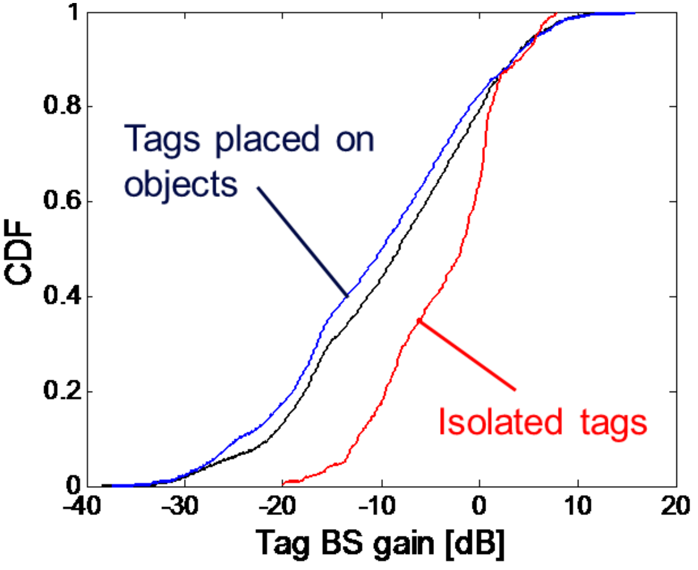
X. Zeng, F. Mani, and A. Sibille, "On the Impact of Antenna Disturbances by Urban Furniture on Deterministic Propagation simulations," IEEE TAP, Vol. 62, N°. 8, Aug. 2014

Propagation-antenna composite channel

Example: UWB RFID backscattering gain statistics

- Full measurements of the antenna radiation pattern (3D, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: supporting objects under an RFID (plates, wood, metal, thin, thick…)
- Backscattering gain (vs. lossless isotropic scatterer) in LOS propagation

➔ Extra loss incurred by the variable disturbances of supporting materials



Propagation-antenna composite channel

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- Full measurements of the antenna radiation pattern (3D, H & V polarizations)
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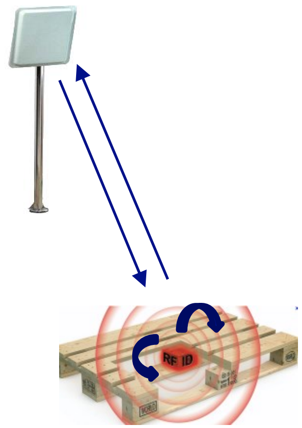
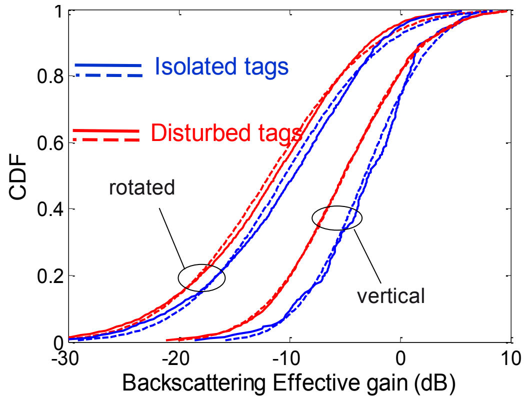
- Backscattering gain (vs. lossless isotropic scatterer) in multipath propagation

➔ Lognormal distribution of the effective gain

➔ Extra loss incurred by the variable disturbances of supporting materials





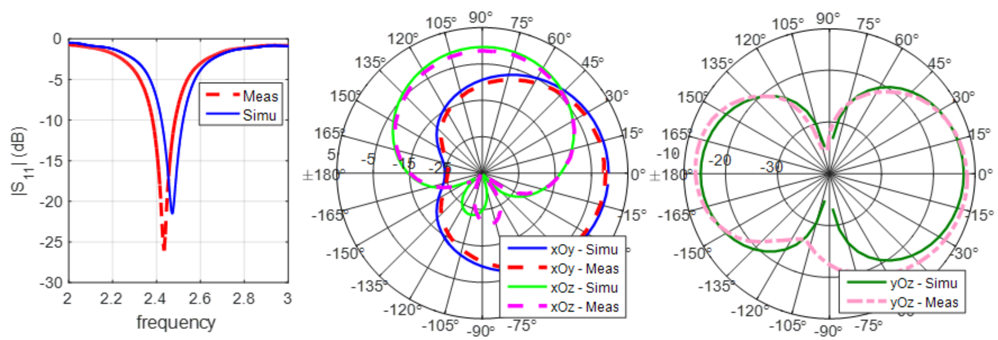
*Alain Sibille, Moussa Sacko, Zeinab Mhanna, Francesco Guidi, and Christophe Roblin, “Joint antenna-channel statistical modelling of UWB backscattering RFID, ICUWB, 20011, Bologna

Propagation-antenna composite channel

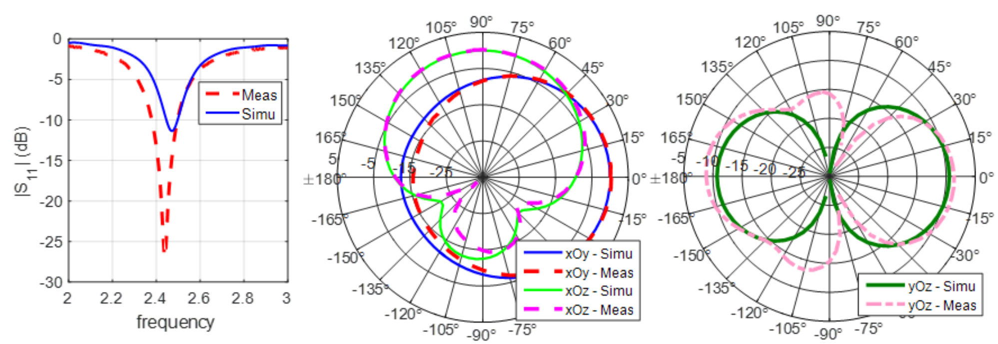
Example: WBAN deformable antenna gain statistics

- Full measurements of the antenna radiation pattern (3D, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: deformable patch antenna on textiles for BANs

Patch 2



Patch 3



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Propagation-antenna composite channel

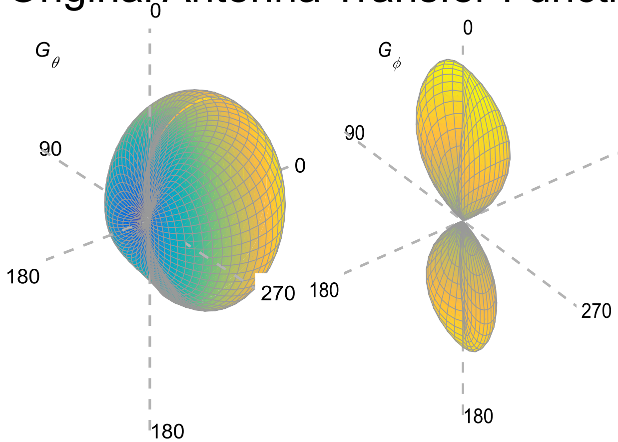
Example: WBAN deformable antenna gain statistics

- Development of a surrogate model:
  1st step: Vector Spherical Harmonics (VSH) expansion

$$\mathcal{H}(f,\hat{\mathbf{r}}) = \mathcal{H}_\theta(f,\hat{\mathbf{r}})\hat{\boldsymbol{\theta}} + \mathcal{H}_\varphi(f,\hat{\mathbf{r}})\hat{\boldsymbol{\varphi}} = \sum_{n=1}^{\infty}\sum_{m=-n}^{n}\sum_{u=1}^{2} H_{nm}^{u}(f)\,\hat{\boldsymbol{\psi}}_{nm}^{u}(\hat{\mathbf{r}})$$

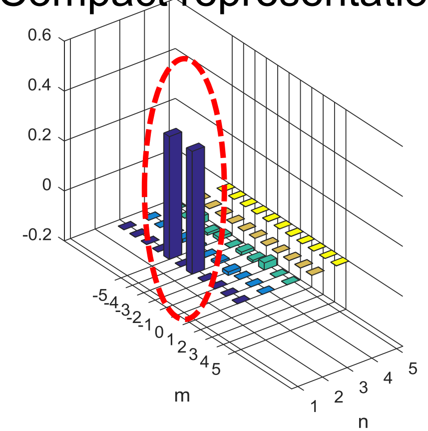
complex coefficients   orthonormal basis

Original Antenna Transfer Function



VSH

Compact representation



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Propagation-antenna composite channel

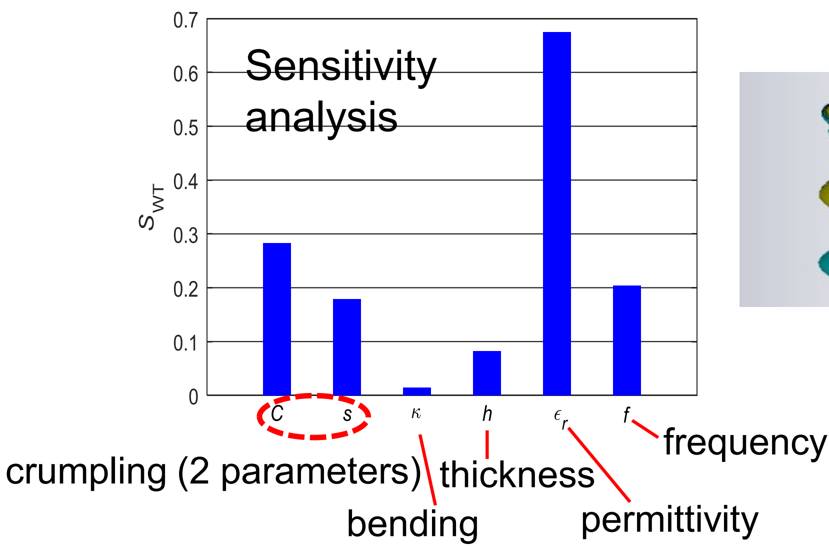
Example: WBAN deformable antenna gain statistics

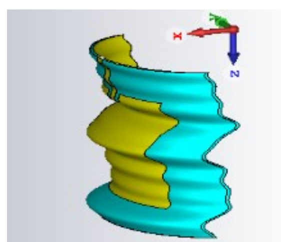
- Development of a surrogate model:
  2nd step: Polynomial chaos expansion (PCE)

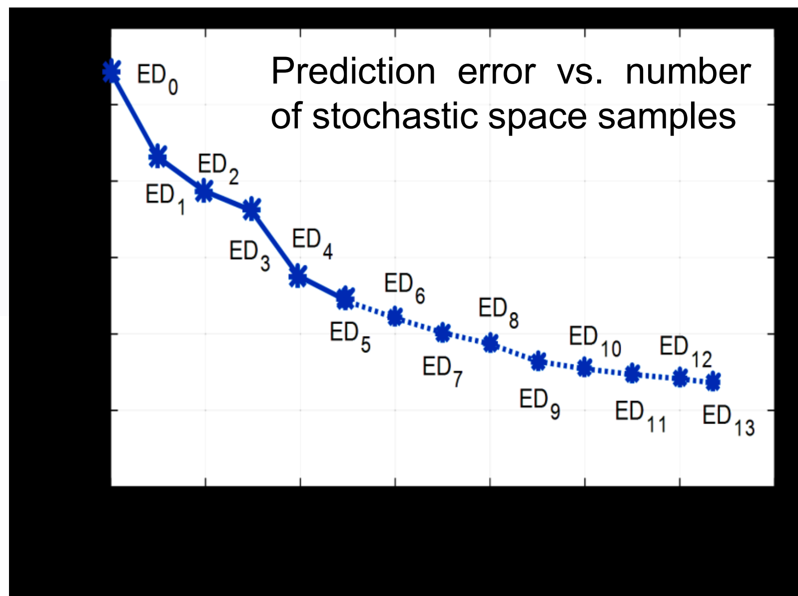
$$Y(\boldsymbol{X}) \approx \hat{\mathrm{M}}(\boldsymbol{X}) = \sum_{\boldsymbol{\alpha} \in \mathrm{N}^M} y_{\boldsymbol{\alpha}} \Phi_{\boldsymbol{\alpha}}(\boldsymbol{X})$$

where X = input (random) parameters and Y = output parameters (VSH coefficients)

And Φ_α = polynomials, which can be selected according to the parameters sensitivity







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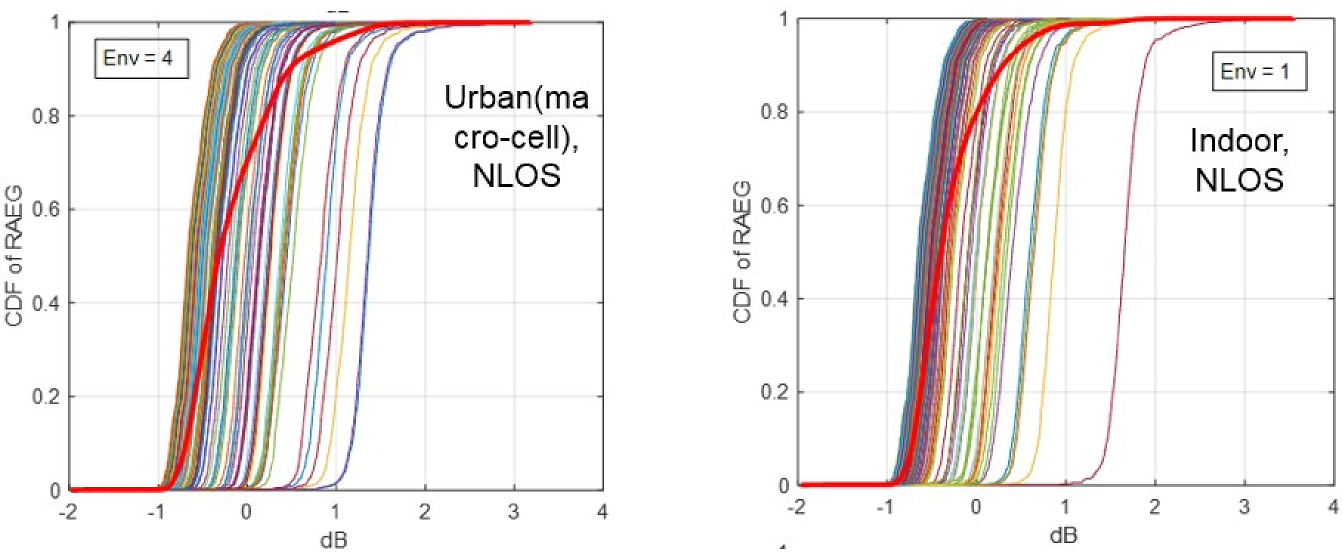
Propagation-antenna composite channel

Example: WBAN deformable effective gain statistics

- surrogate model of the deformable patch antennas
- Local subset of the WINNER 2 propagation channel model

➔ Relative Averaged Effective Gain compared to the fixed flat antenna



Colored thin lines: CDF of 1 CH x 1000 random Ants. **Red thick line: CDF of 100 CH x 1000 random Ants.**

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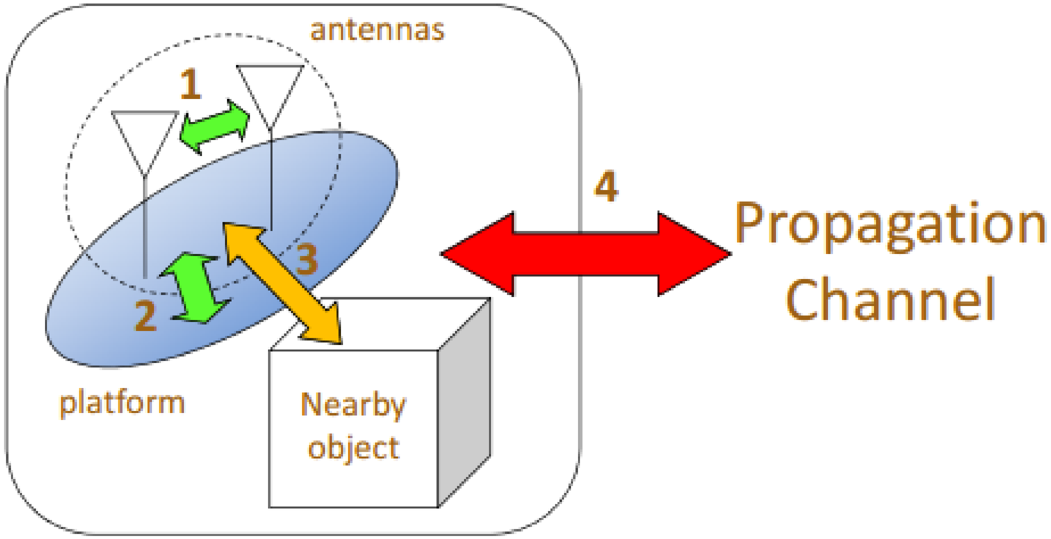
Propagation-antenna composite channel

- **Example: MIMO terminal statistical performance**

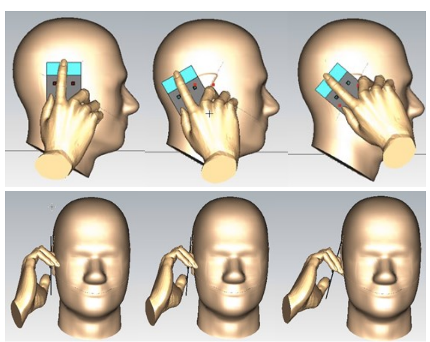


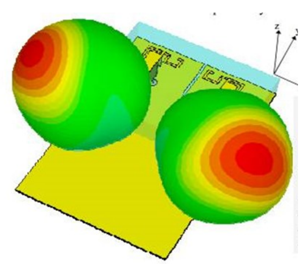
Credits: Buon Kiong Lau, "Terminal Antenna Design Paradigms for Future Wireless", IC1004 13th MCM, Valencia, May 5, 2015

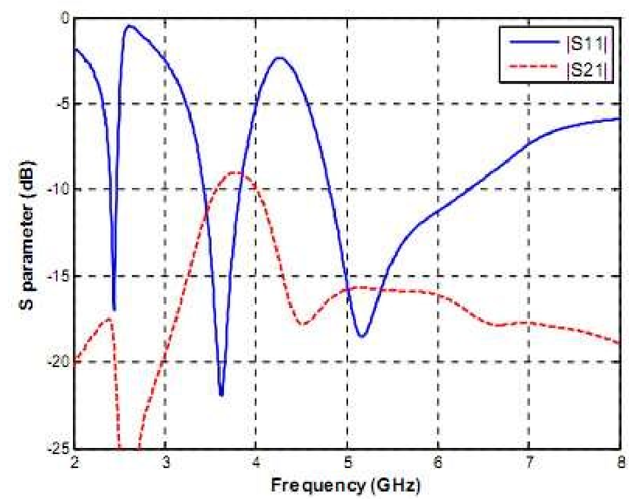
Propagation-antenna composite channel

Example: MIMO terminal statistical performance

- Partial measurements of the antenna radiation patterns (2D, H & V polarizations)
- Involvement of a « typical » close environment in a limited set of variable parameters: phantom head, a few orientations/tilt of the handset in talk mode
- Model of the local multipath propagation channel (stochastic, e.g. extracted from standard propagation channel models)







A. Sibille & J. Braga, “MIMO terminals performance evaluation in a local propagation context”, URSI AT-RASC, Gran Canaria, May 2015

Propagation-antenna composite channel

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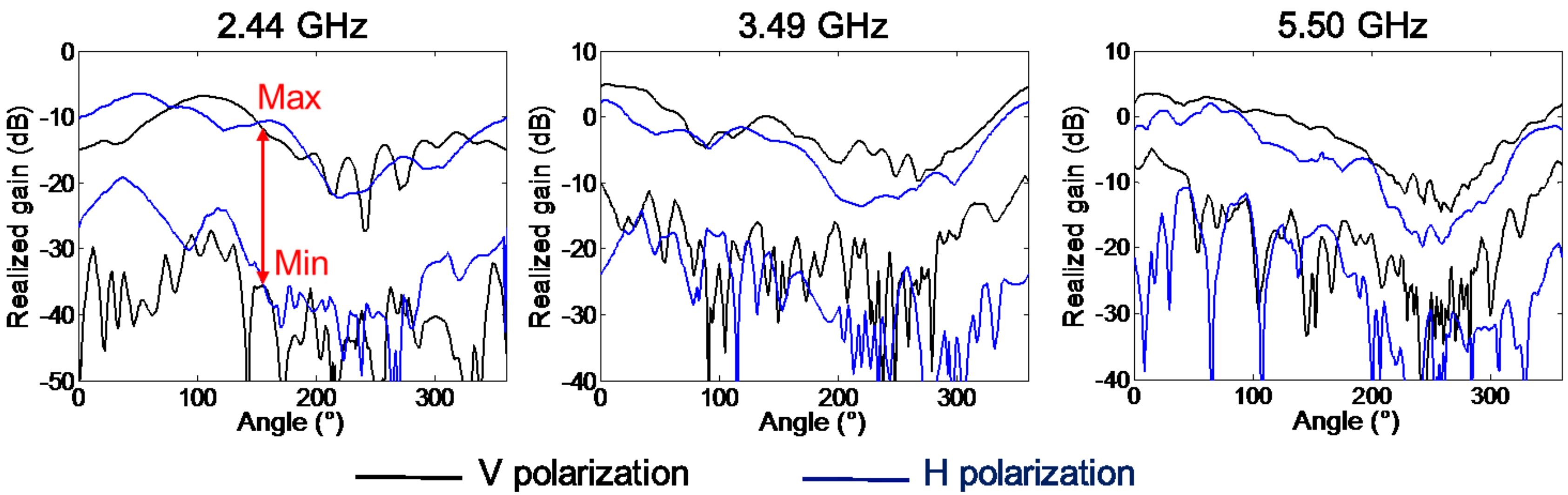

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Comparison

- i.i.d. capacity (ideal uncorrelated antennas)
- "exact" link performance computed with full complex antenna patterns and multipath propagation channel
- **Randomized orientation, low-pass angle filtered antenna patterns**, two approximations for the phase correlation matrix
  - Computed from each detailed propagation channel realization
  - Computed from the mean power angular spectrum (PAS)

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Propagation-antenna composite channel

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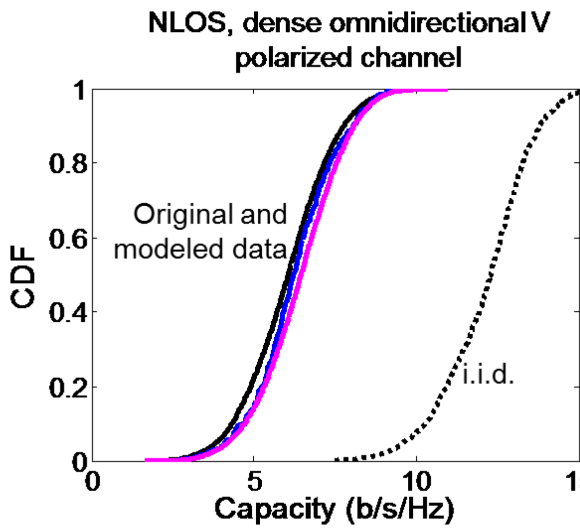

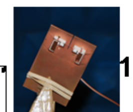

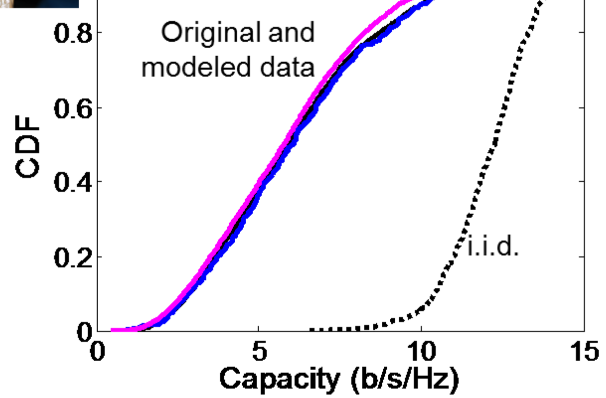

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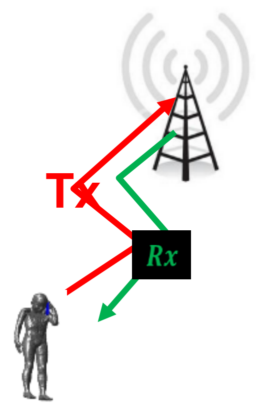
Modeling of exposure to EM waves

Uplink vs. downlink exposure

- Uplink: concentrated EM power absorbed from the local transmitter ; typically expressed through the Specific absorption rate (SAR, W/kg):

$$\mathrm{SAR} = \frac{1}{V}\int_{\mathrm{sample}} \frac{\sigma(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2}{\rho(\mathbf{r})} d\mathbf{r}$$

- Downlink: whole body absorbed EM power from the distant transmitter



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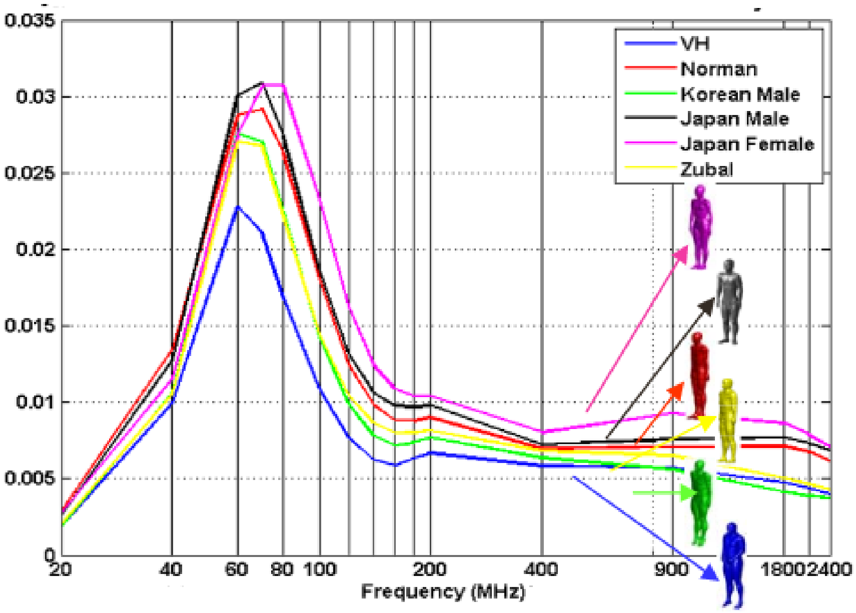
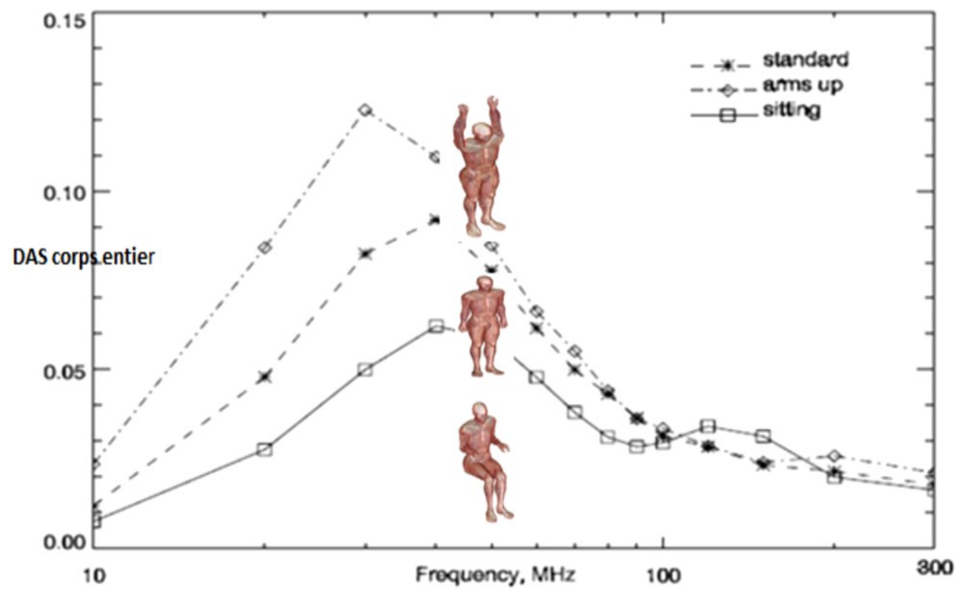
Modeling of exposure to EM waves

- **Variability: morphology, posture (downlink whole body SAR from front wave)**





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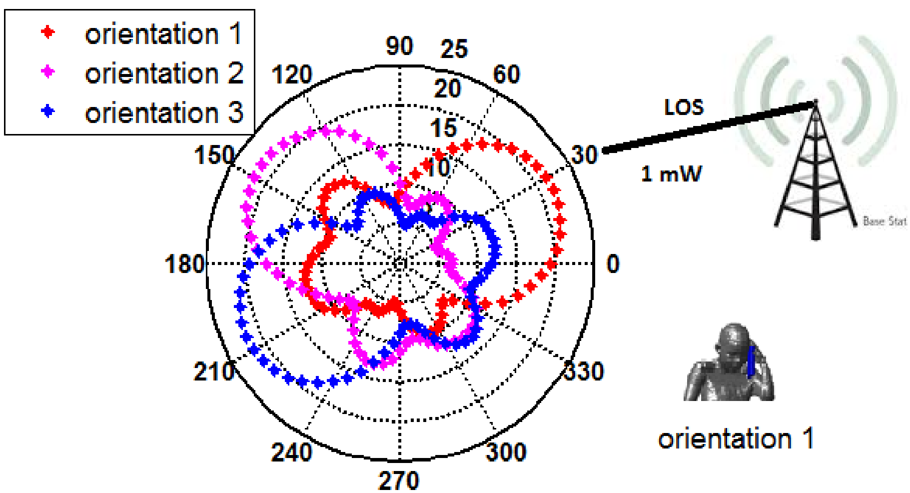
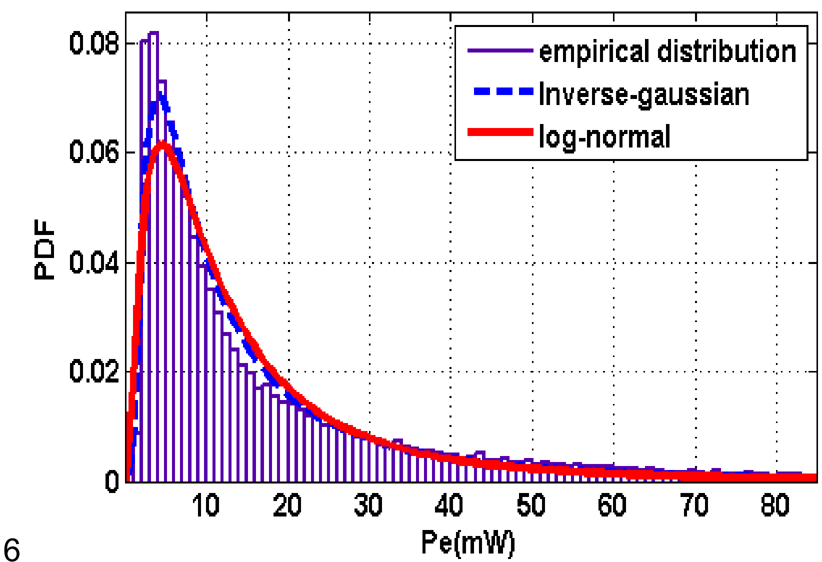
Modeling of exposure to EM waves

- **Statistical antenna-propagation issues (uplink)**
  - Full simulation of the antenna radiation pattern (3D, H & V polarizations) in presence of a full phantom (1 or 2 mm resolution)
  - Varying directional match between the antenna pattern and the LOS propagation (cf. transmit power control and constrained received power)

➔ ~ Lognormal distribution of the radiated (and absorbed) power (fixed device/body)





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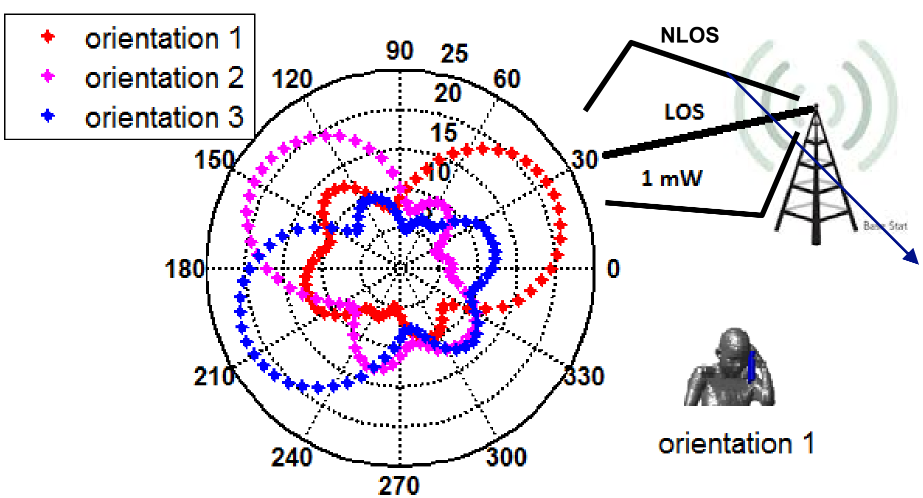
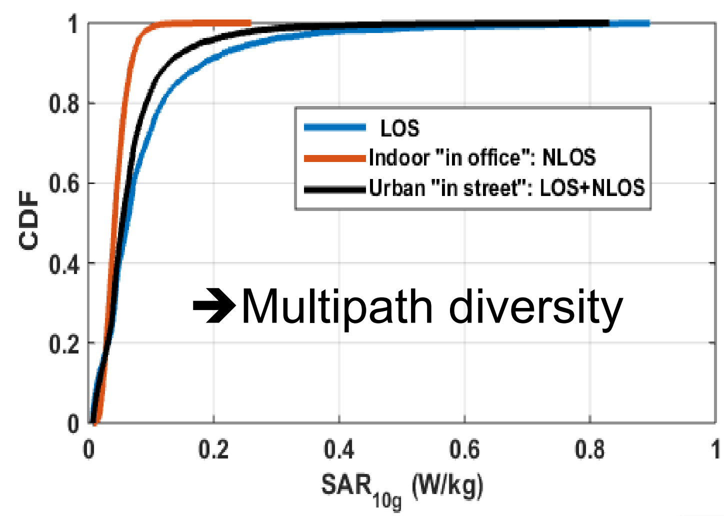
Modeling of exposure to EM waves

Statistical antenna-propagation issues (uplink)

- Full simulation of the antenna radiation pattern (3D, H & V polarizations) in presence of a full phantom (1 or 2 mm resolution)
- Varying directional match between the antenna pattern and the directional channel scenario (cf. transmit power control and constrained received power)

➔ ~ Multipath diversity reducing the spread of the SAR





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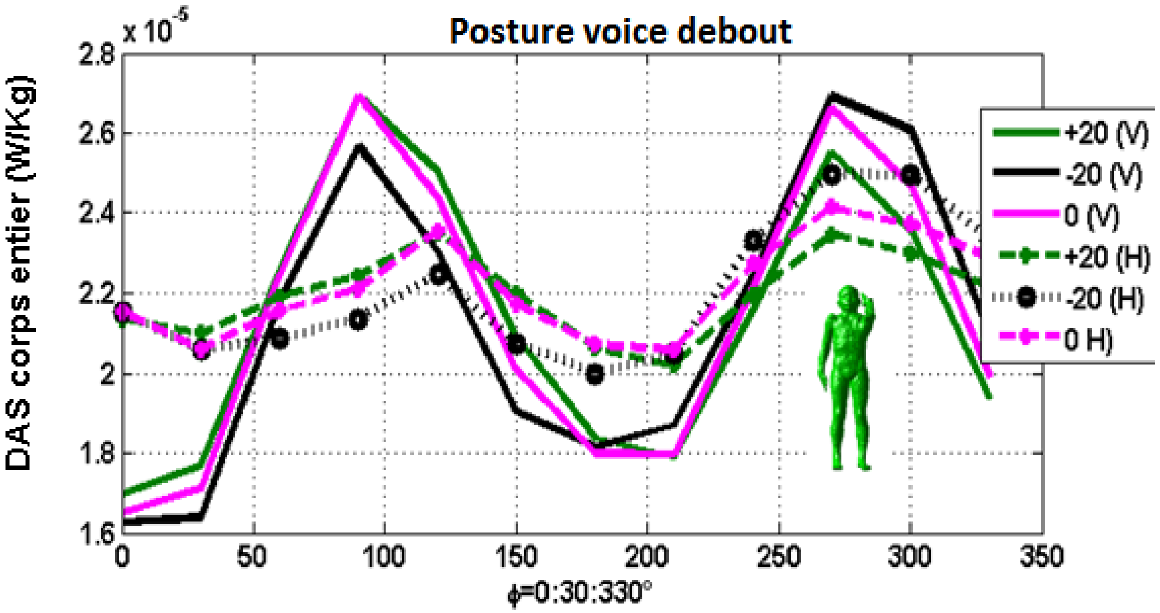
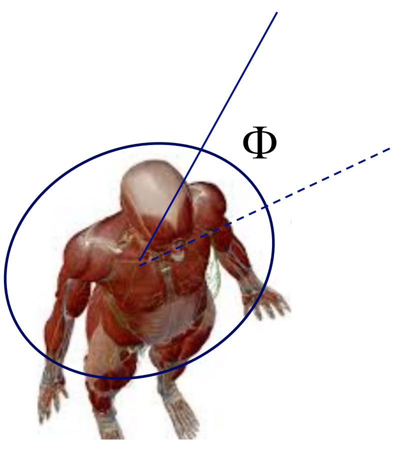
Modeling of exposure to EM waves

- **Exposure variability from the downlink**
  - Full simulation of the whole body SAR (1 or 2 mm resolution)
  - ➔ Strong azimuth and polarization dependence (single wave)





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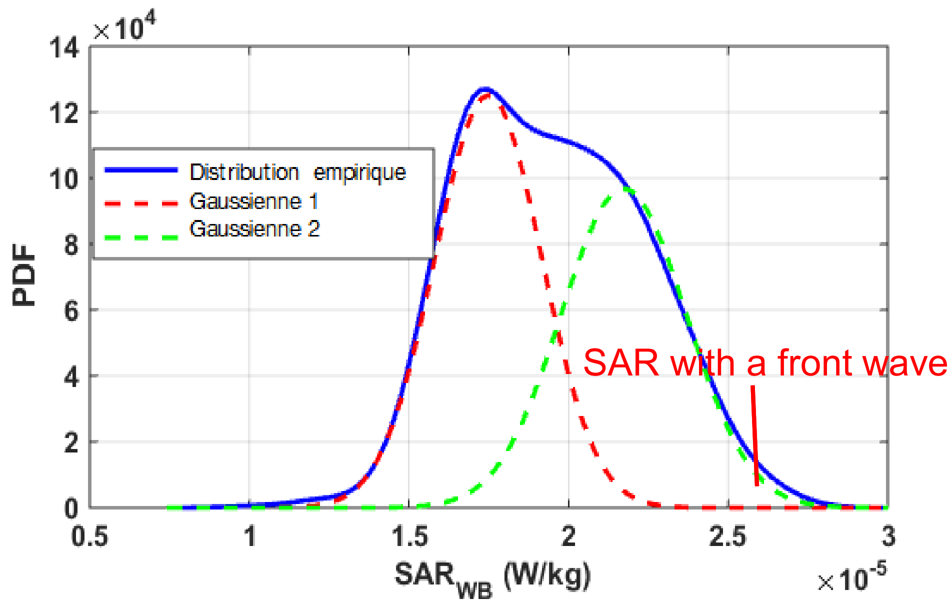
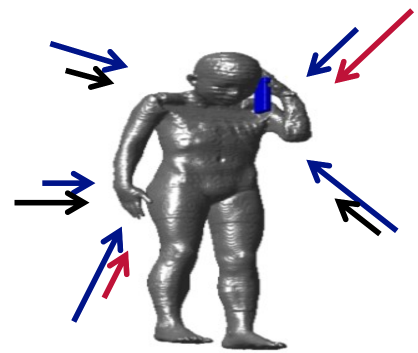
Modeling of exposure to EM waves

Exposure variability from the downlink

- Full simulation of the whole body SAR (1 or 2 mm resolution)
- 5 H/V waves scenario: 25 input parameters (amplitudes, phase, angles)

➔ Double moded distribution from a reduced set of samples (1000, Latin hypercube)





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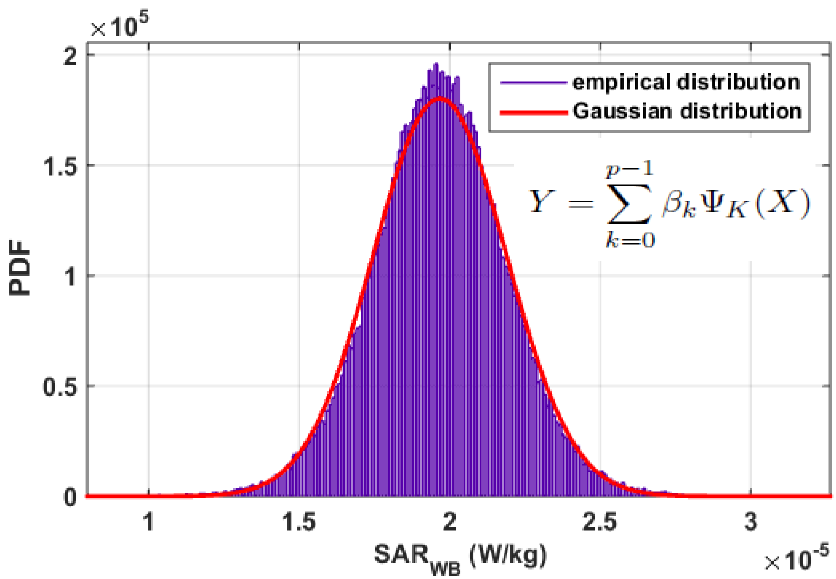
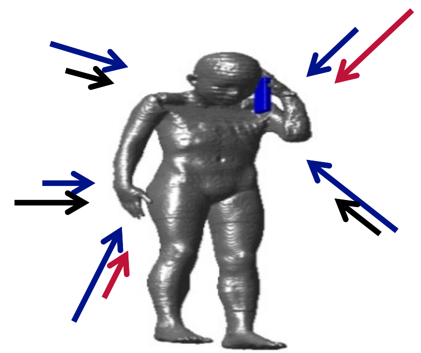
Modeling of exposure to EM waves

Exposure variability from the downlink

- Full simulation of the whole body SAR (1 or 2 mm resolution)
- 5 H/V waves scenario: 25 input parameters (amplitudes, phase, angles)

➔ Single moded (Gaussian) distribution from a large set of samples (100000) based on a surrogate model (PCE)





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Conclusion

- Electromagnetism does not differ from many areas of science/technology: many (many many…) uncertainties and sources of randomness dominate physical properties and performance of systems
- Tracking these sources and modelling them/their effects allows to better understand/track what's going on, useable in various ways
- Given the fundamental complexity we face, the game is to work progressively and to find methods to simplify/approximate the problems at hand