LABORATOIRE ÉLECTRONIQUE, SYSTÈMES DE COMMUNICATION ET MICROSYSTÈMES

Sous la co-tutelle de :
CNAM
CNRS
ESIEE PARIS
UPEM • UNIVERSITÉ PARIS-EST MARNE-LA-VALLÉE

Approche statistique appliquée au modèle de couplage électromagnétique d'étiquettes RFID aléatoirement réparties

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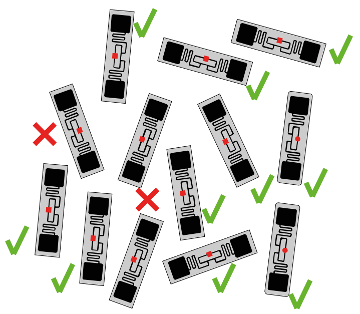
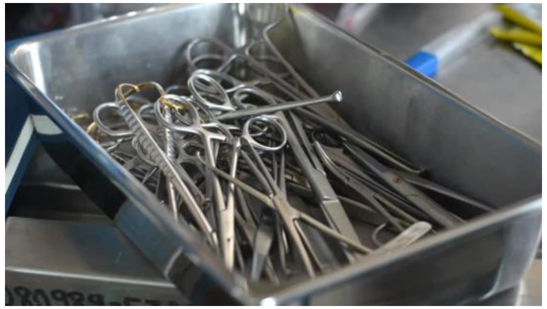
Context

- Complex environment
  - The tag antenna is surrounded by **other tags** in a high density of radiating elements.
  - The close **environment** of the tag antenna is partially known or known with uncertainties.
  - High impact on the RFID communication link budget
  - Random phenomena / statistical approach



High density context

Wet versus dry clothes



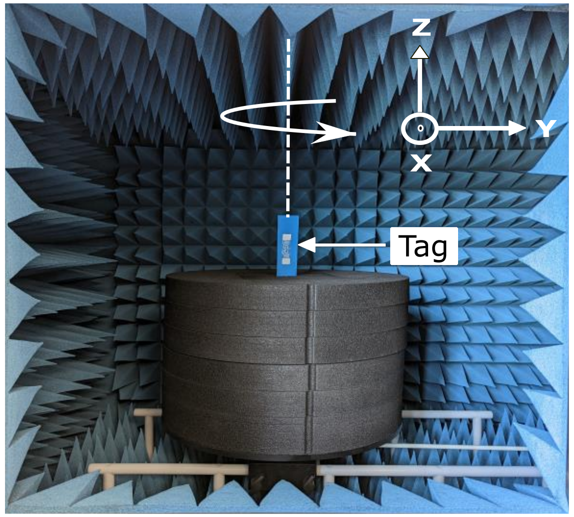
Unsorted surgical instruments

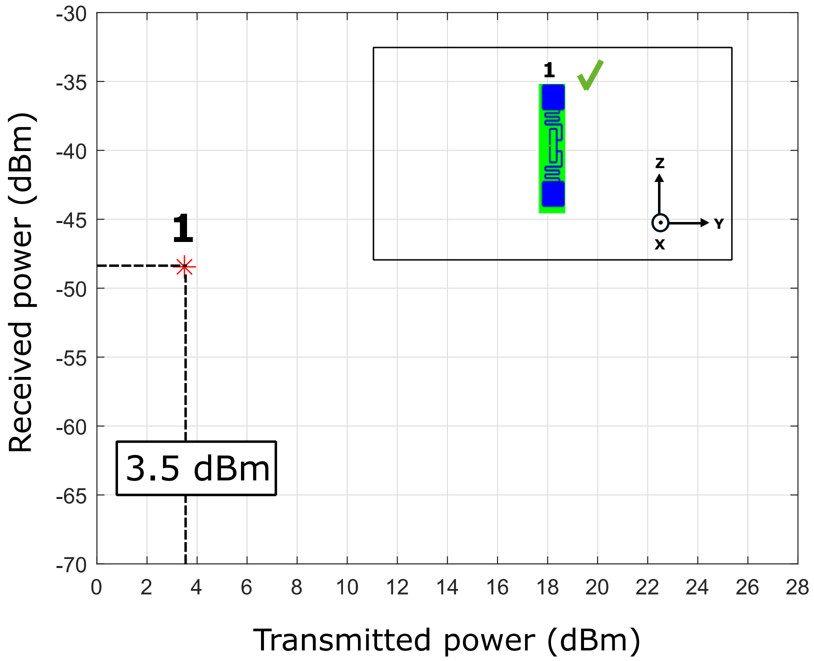
Challenge:

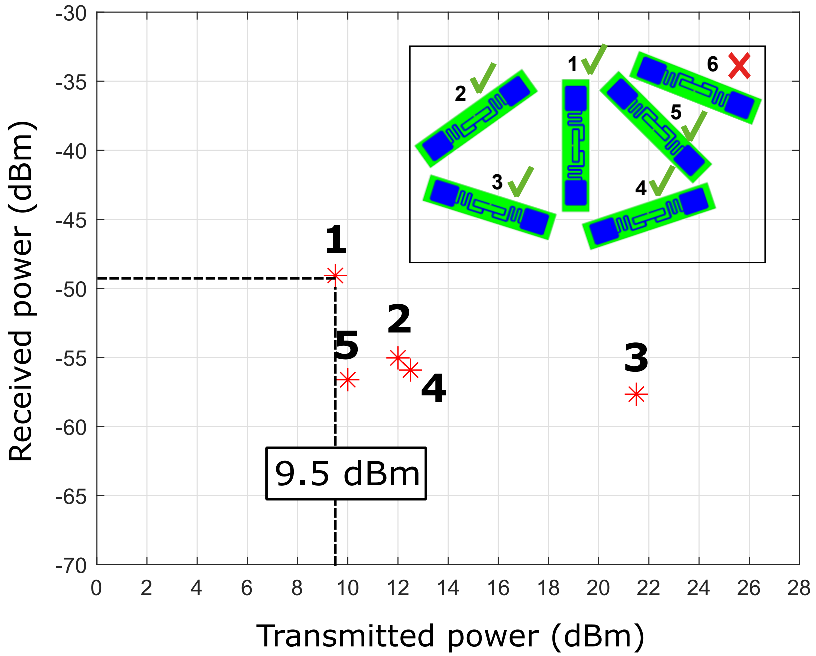
Introduce an efficient prediction model of an RFID system including all interactions of the close environment

Empirical observation

- Measurements in Voyantic Tagformance







Turn-on power of tags are modified by the close surrounding tags.

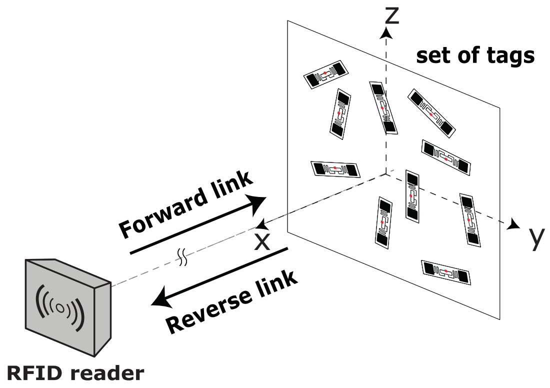
Random configuration → Statistical analysis of the impact

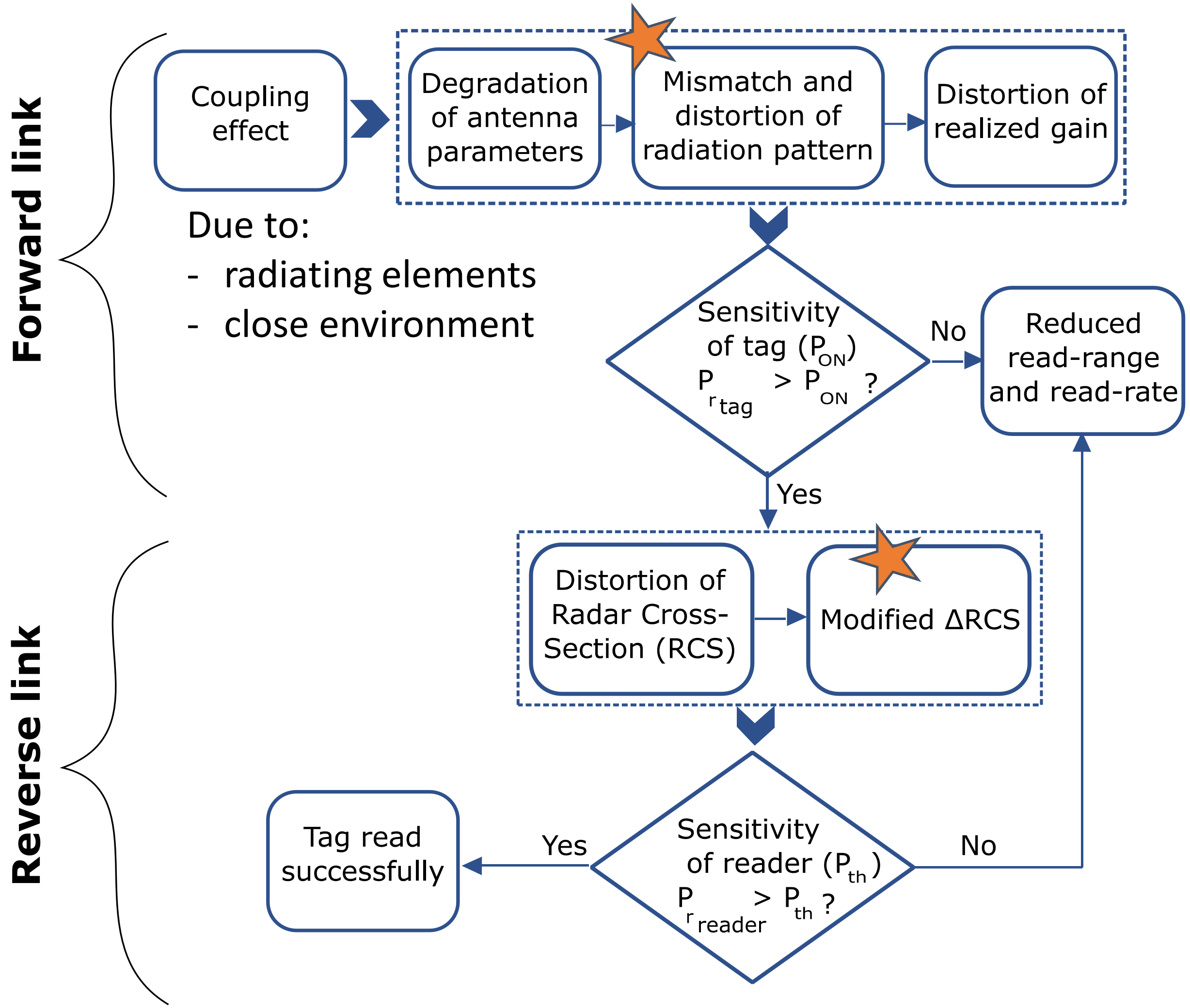
How to model?

Outline

- Methodology and hypothesis
- Physical models and validation process
- Two examples of statistical analysis:
  - Mismatch
  - RCS / ΔRCS
- Conclusion and future work

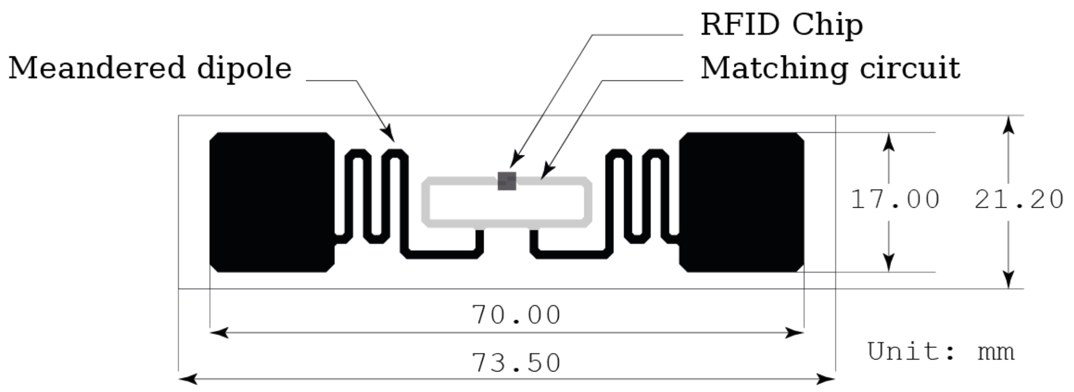
Problem decomposition



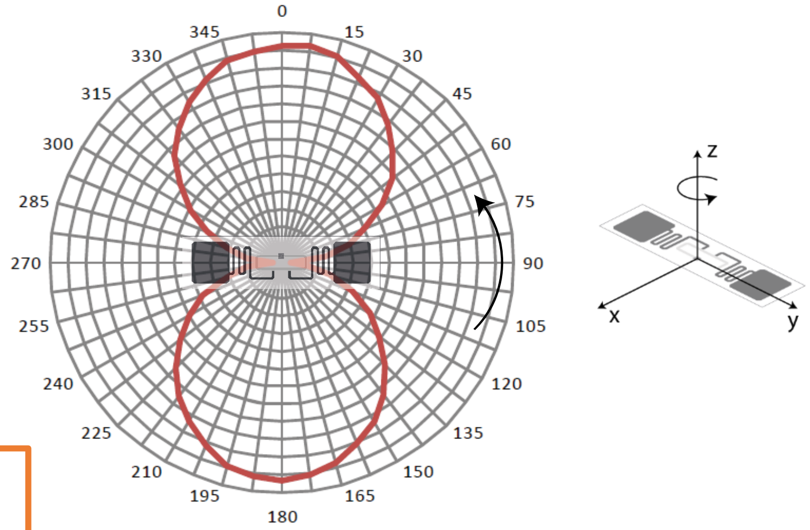


UHF RFID TAG

- ALN-9262 Tag
  - Worldwide RFID UHF operation (840-960MHz)



- Isolated angular sensitivity (extracted from datasheet)
  - Function of the antenna pattern
  - Similar to half-wave dipole pattern



- Hypothesis

> We assume that a canonical dipole is a good candidate to describe the behaviour of a tag antenna.

Methodology

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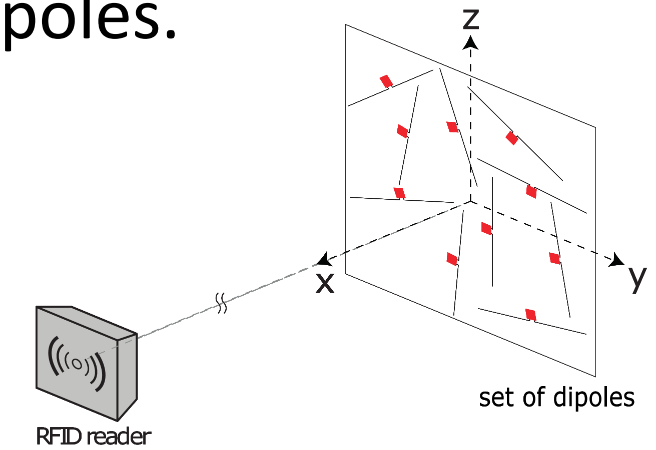
- RFID system modelled by a set of randomly distributed dipoles.



<u>Input variables</u>

- Dipole position
- Dipole orientation
- Density
- Close environment properties

→ **Physical modelling** →

Numerical methods
Asymptotic analytical methods

<u>Output variables</u>

Matching properties
- Input impedance
- Reflection coefficient

Radiation properties
- Radiation pattern
- Gain
- Radar cross section

System KPI
- Read rate
- Read range

Physical models

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Asymptotic method

- IEMF (Induced Electro-Motive Force)
  - Reciprocity theorem
  - Self and mutual impedance
  - Thin dipoles (diameter < $10^{-3}\lambda$)
  - Application to 2 dipoles
- Extended IEMF
  - Arbitrary positioned and oriented dipoles
  - Any number of dipoles provided that the minimum scattering condition is satisfied

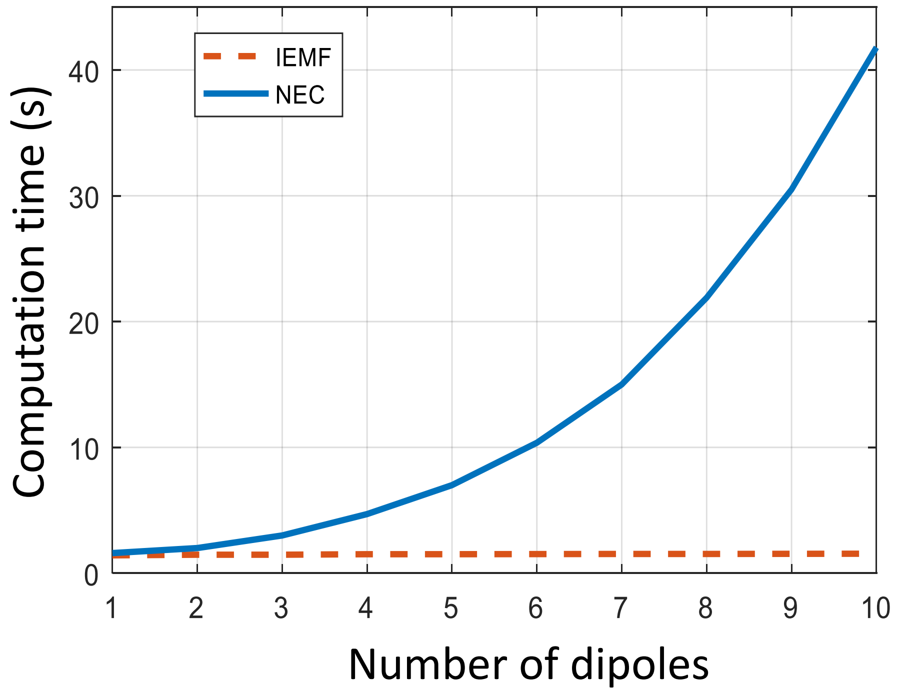
Numerical methods

- NEC (Numerical Electromagnetic Code)
  - Method of Moments
  - Faster than a full-wave simulator
  - Wire antennas
  - Application to thin and thick dipoles
- HFSS (High Frequency Structure Simulation)
  - Finite Element Method
  - Full-wave EM simulator
  - Any structure
  - Application to tag antennas

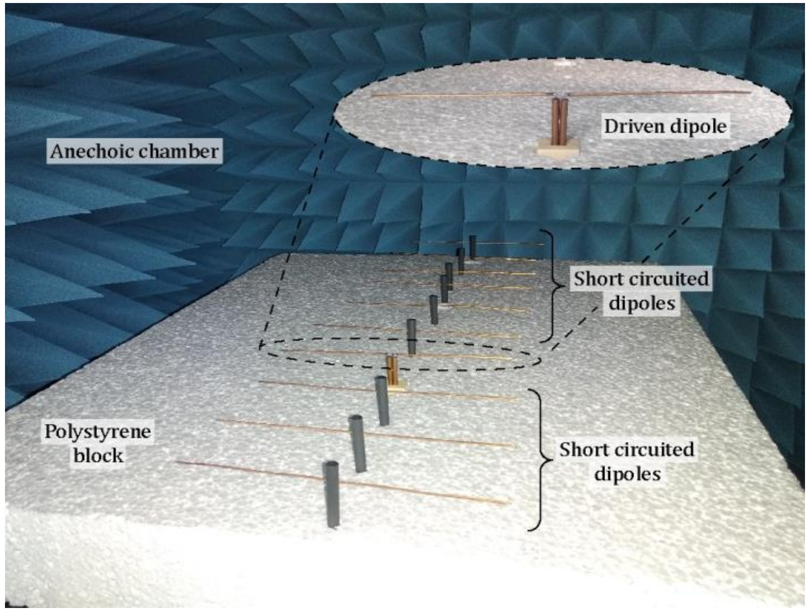
Validation process – Simulation

- Choice of validation tools:
  - Thin dipoles
    - IEMF
    - NEC
  - Thick dipoles
    - NEC
    - Measurement
  - Tag antennas
    - HFSS
    - Measurement

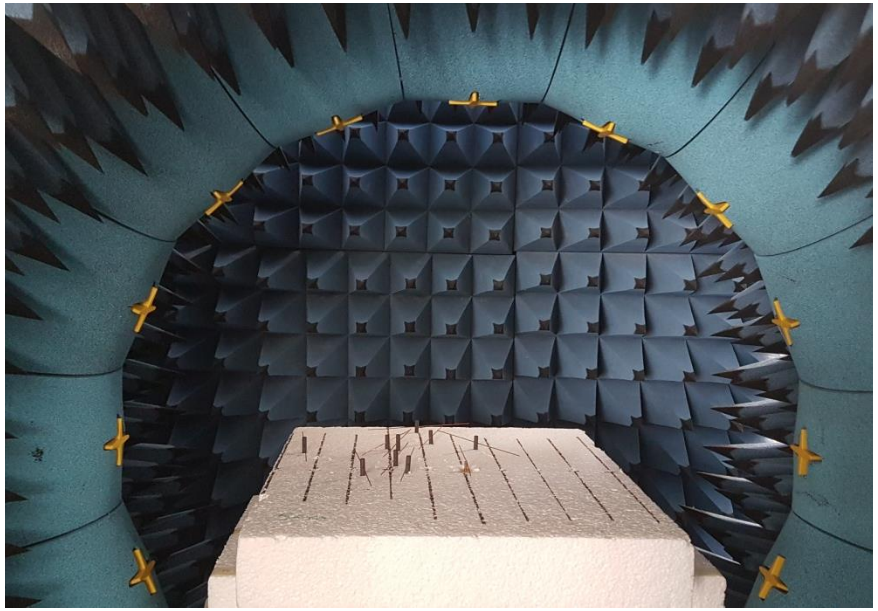
- Comparison of computation time



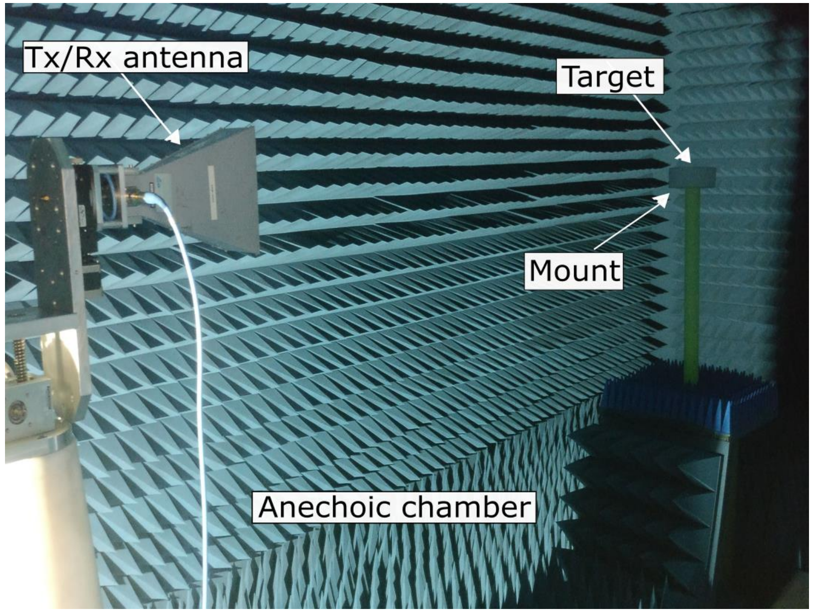
Validation process – Measurements



Impedance measurement
Anechoic chamber, ESYCOM



Radiation pattern measurement
Starlab, Télécom Paris



RCS measurement
Anechoic chamber, ESYCOM

Input parameters

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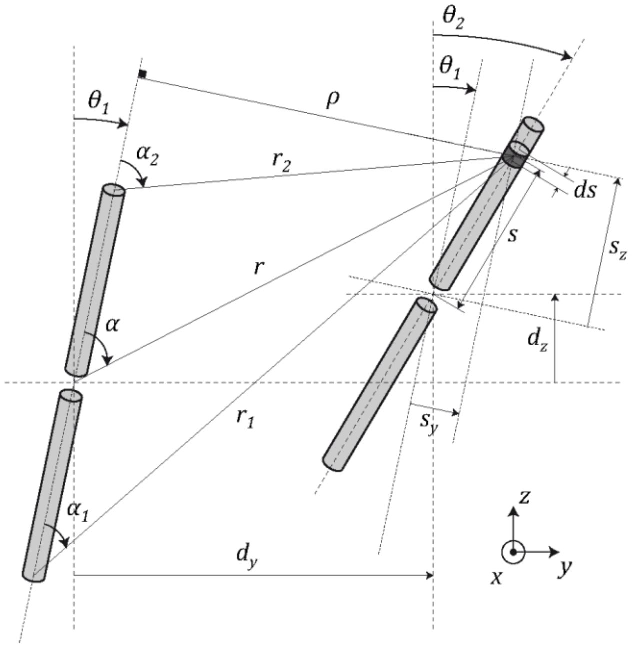
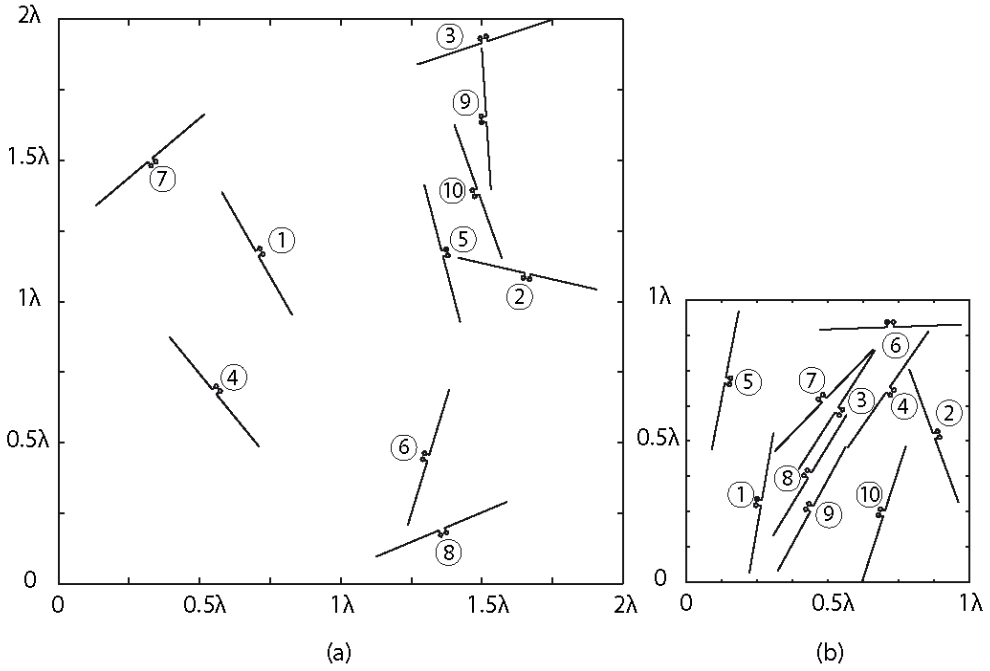
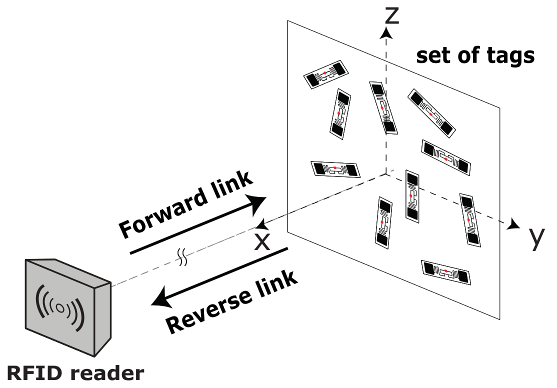
- For each antenna dipole
  - Position
  - Orientation
  - Load

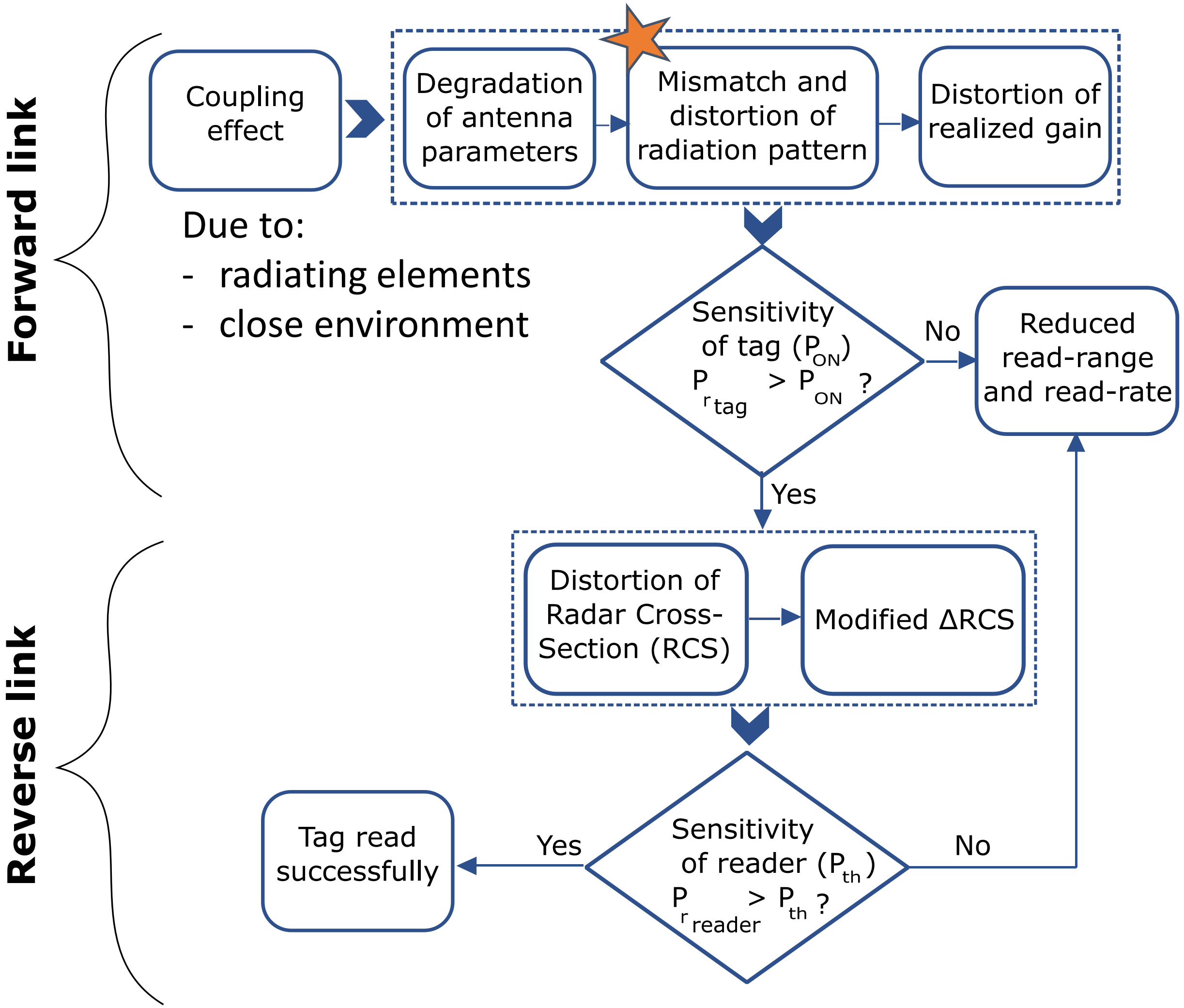


- For a group of dipoles
  - Number
  - Distribution area



Problem decomposition





Experimental design

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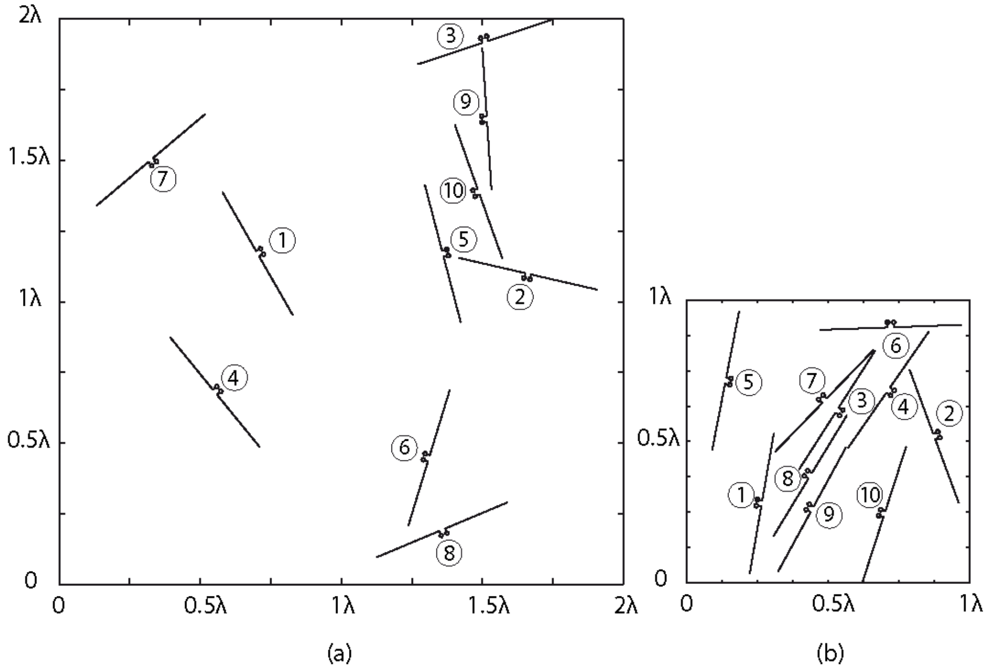
- Number of dipoles: 10
- Distribution area: bxb
- Number of trials: 400 LHS
  - 4000 generated samples
  - Convergence verified
- Loads of surrounding dipoles: Matched and Short-Circuited
- IEMF and NEC
- Thin and thick dipoles



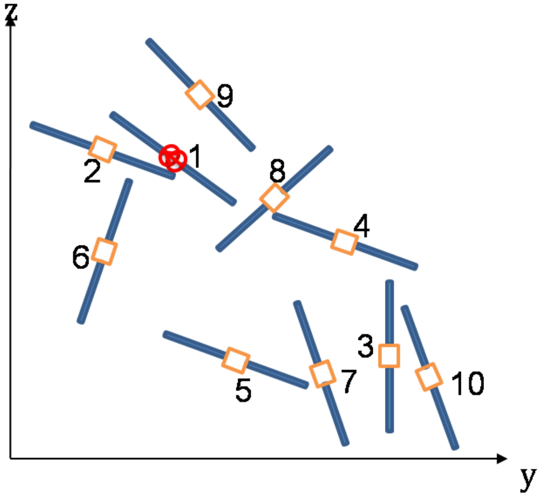
Mismatch analysis – Load/Density

- Reflection coefficient

$$\Gamma_{in} = \frac{Z_{in} - Z_{ref}^{*}}{Z_{in} + Z_{ref}}$$

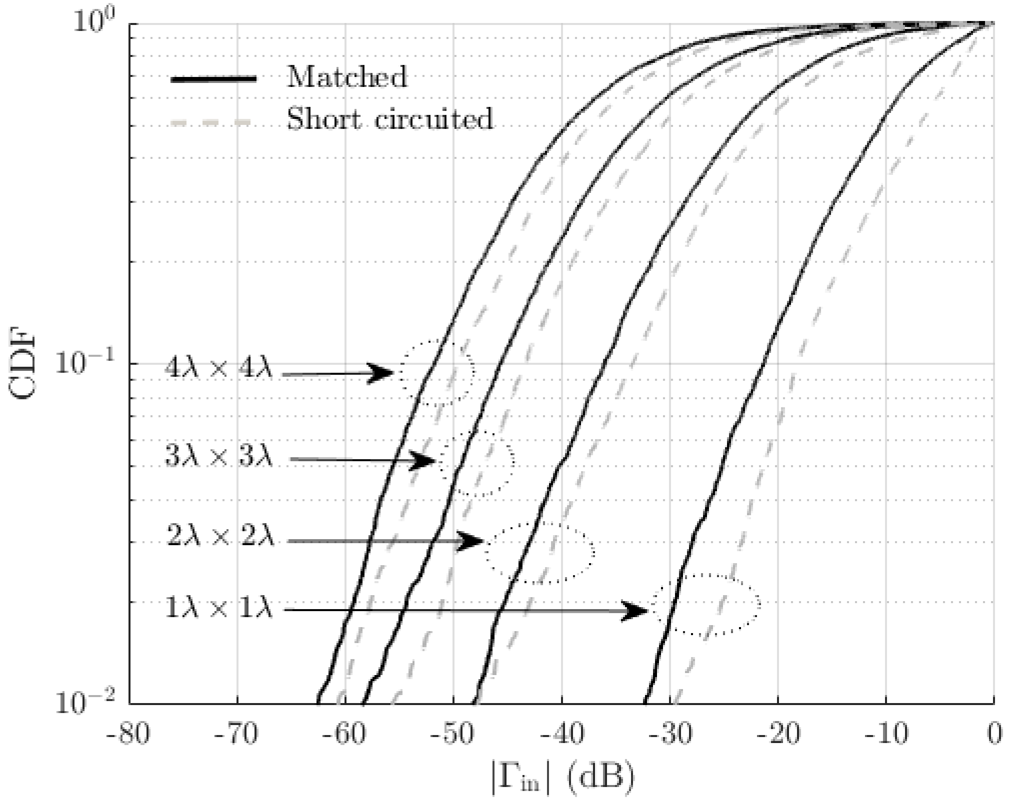
Z_{in} Input impedance

Z_{ref} Reference impedance: Z_{11}



|Γin| <-10 dB

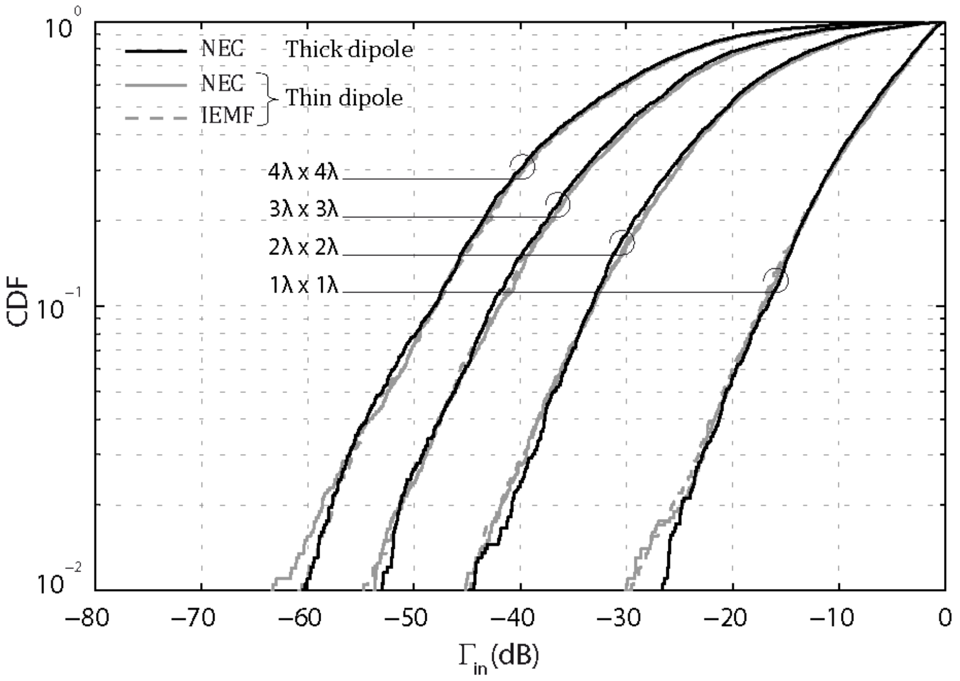
Load	1λx1λ	2λx2λ	3λx3λ	4λx4λ
SC	35%	87%	97%	98%
Matched	54%	92%	98%	99%



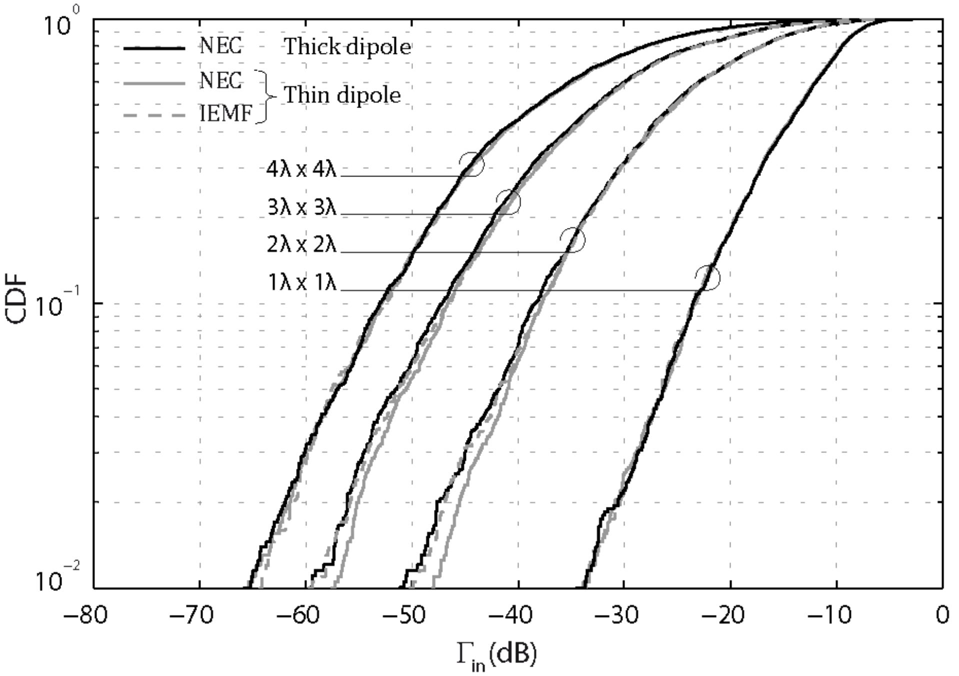
Mismatch analysis – Thin vs. Thick

- Cumulative distribution function
  - $Z_{11\text{-thin}} \neq Z_{11\text{-thick}}$

Matched loads



Short-circuit

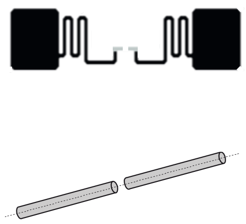


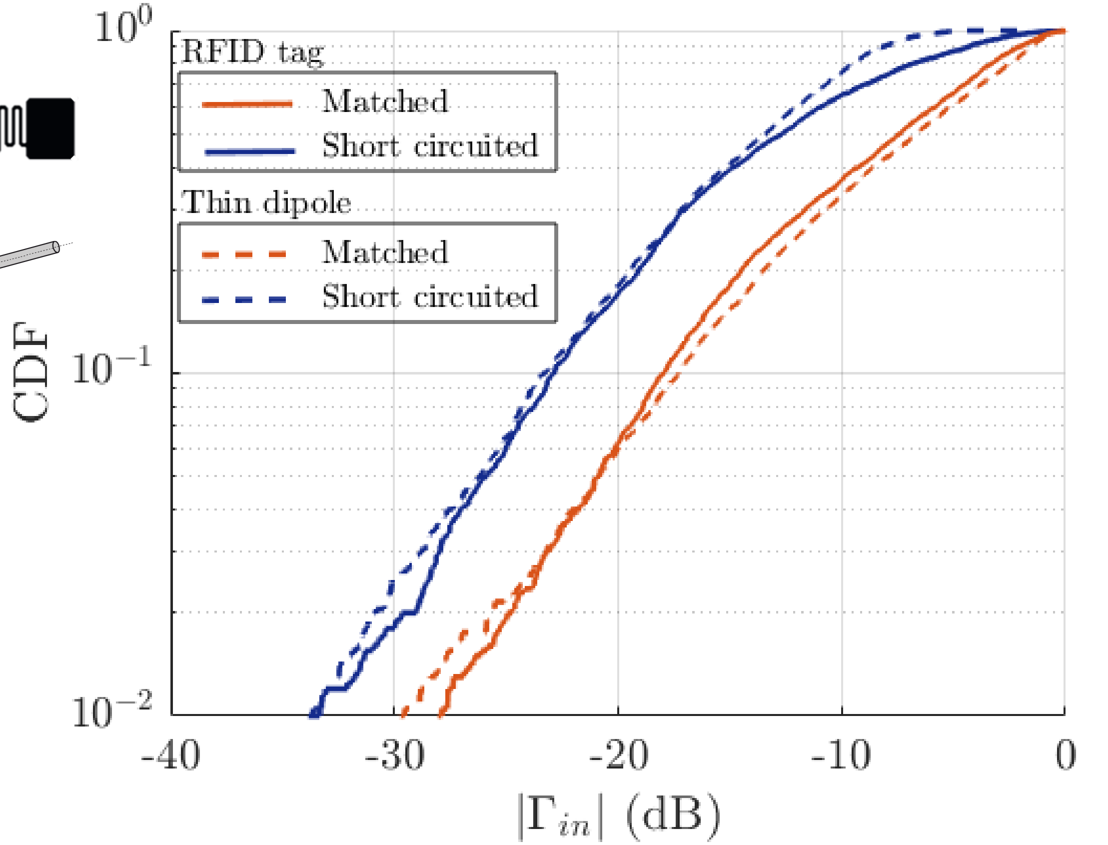
The statistical behavior between thin and thick dipoles seems to be similar.

Mismatch analysis – Tags

- RFID tag antenna without the matching circuit

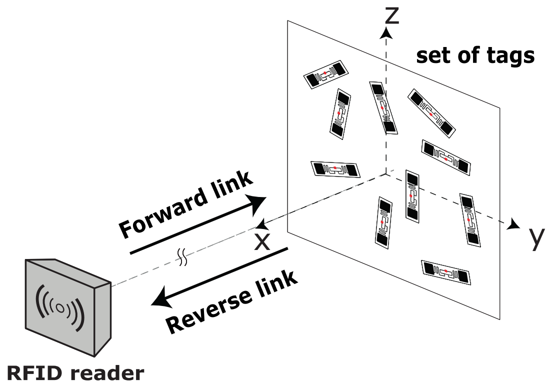
- Experimental design:
  - Distribution surface: 1λ× 1λ
  - Same configurations as dipoles
  - Loads: matched, short-circuit

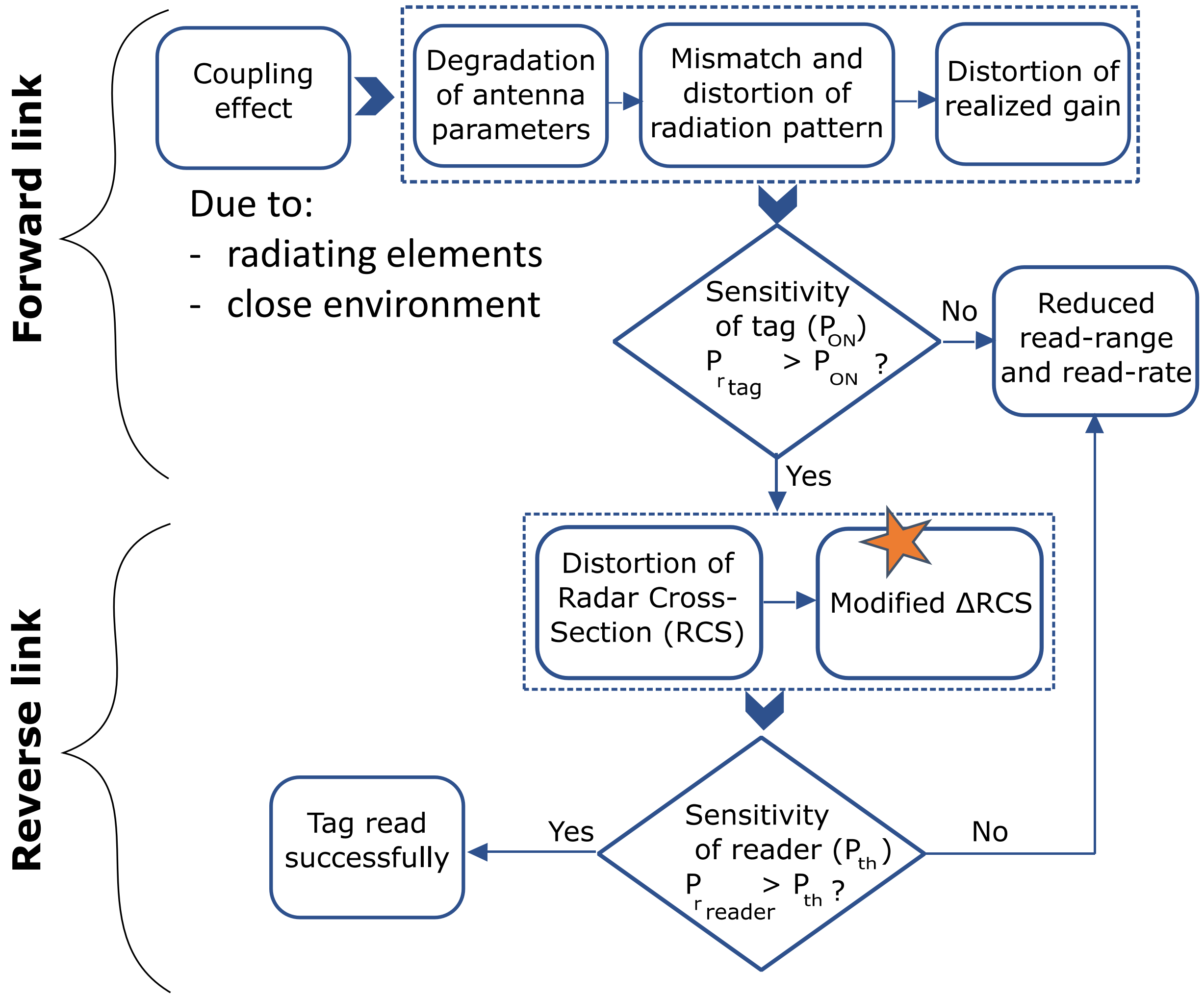




The statistical behavior of the tag antennas can be modeled by that of the simple dipoles.

Problem decomposition





Monostatic RCS

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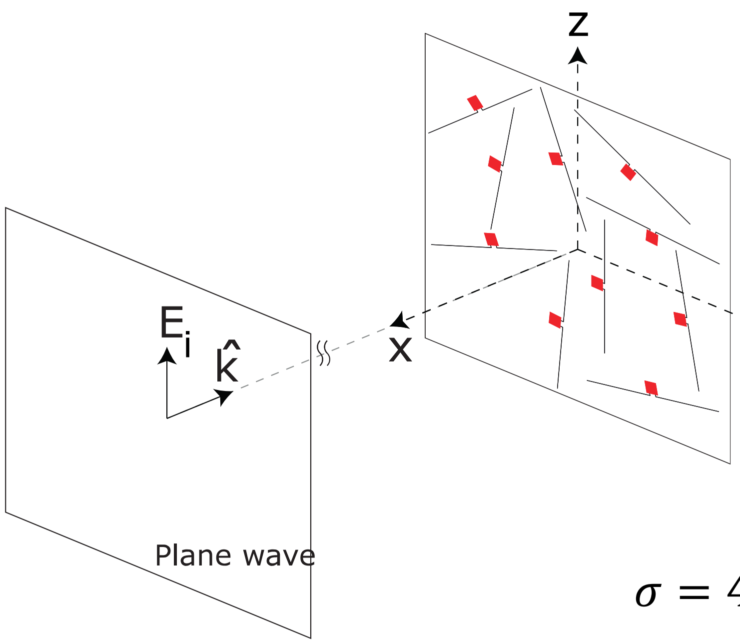
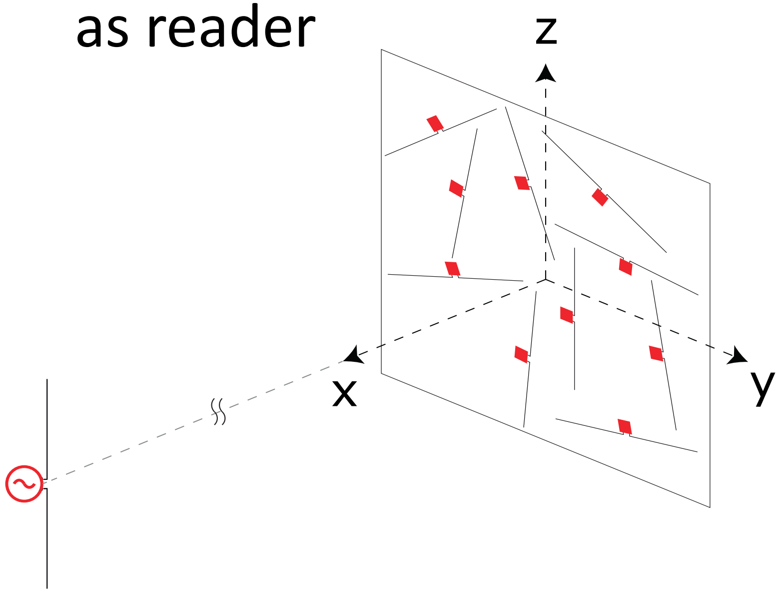
- Back-scatterd field
  - Simulation
  - Excite N dipoles with incident electromagnetic field $\mathbf{E_i}$



$$\sigma = 4\pi r^2 \frac{|\mathbf{E_s}|^2}{|\mathbf{E_i}|^2}$$

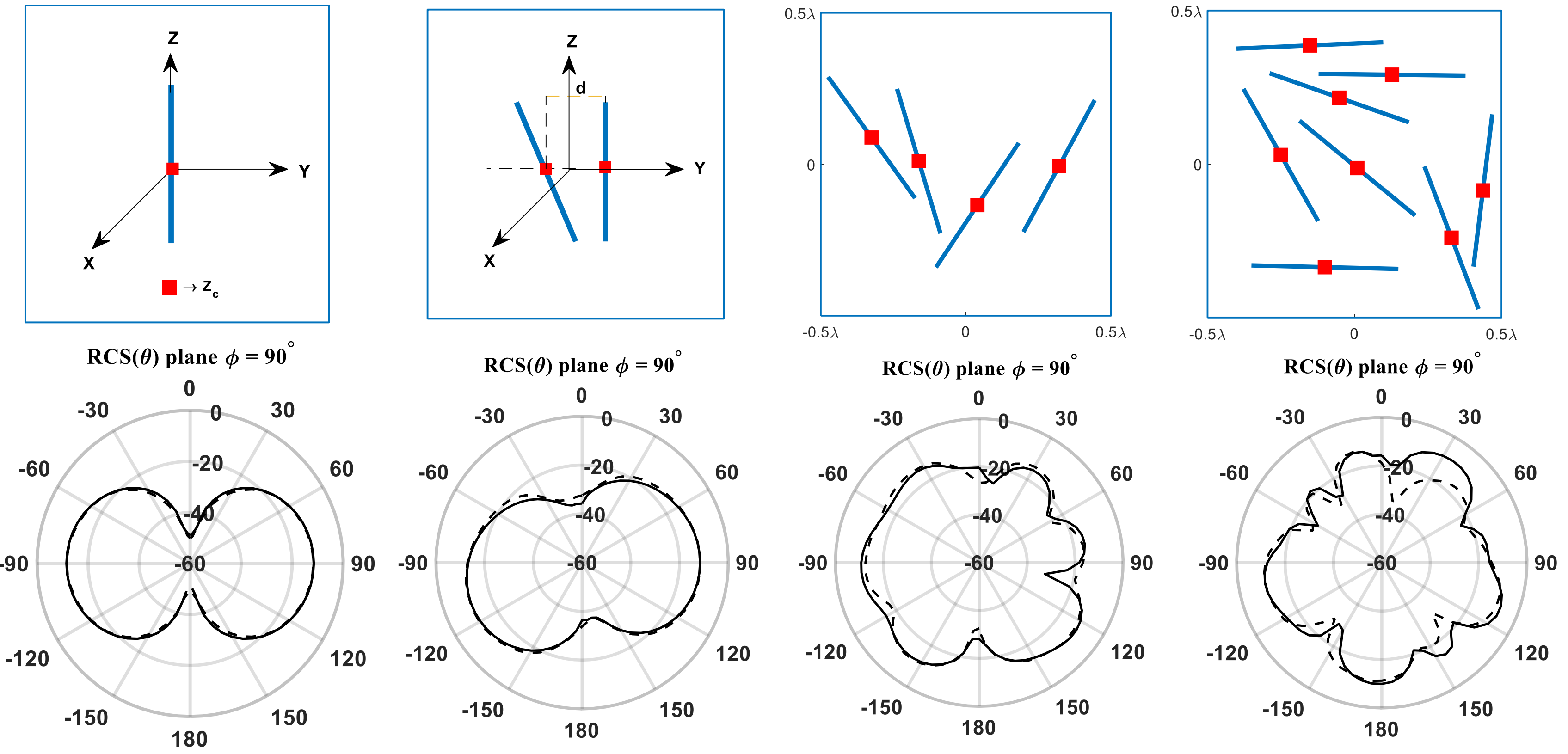
- Radar equation
  - Measurement or simulation
  - Excite N dipoles using a dipole acting as reader



$$\sigma = \left|S_{11}^{+\text{target}} - S_{11}^{-\text{target}}\right|^2 \frac{(4\pi)^3 r^4}{{G_t}^2 \lambda^2}$$

RCS – Simulation vs. measurement

- Loaded half-wave dipoles
- Diameter = 1 mm
- f = 866 MHz
- Z_c = 0



RCS by:

——— back-scattered field (NEC)

- - - - radar equation (measurement)

Experimental design

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- Number of dipoles: 10
- Distribution area: 1λx1λ, 2λx2λ
- Number of trials: 2000
- Loads of surrounding dipoles: Matched ($Z_c = Z_{11}^*$), short-Circuited ($Z_c = 0$)
- NEC
- Dipole diameter: $10^{-6}\lambda$, $10^{-3}\lambda$, $10^{-2}\lambda$
- Observation plane: ϕ_{E_i} = 0° , θ_{E_i} = 90°

RCS analysis

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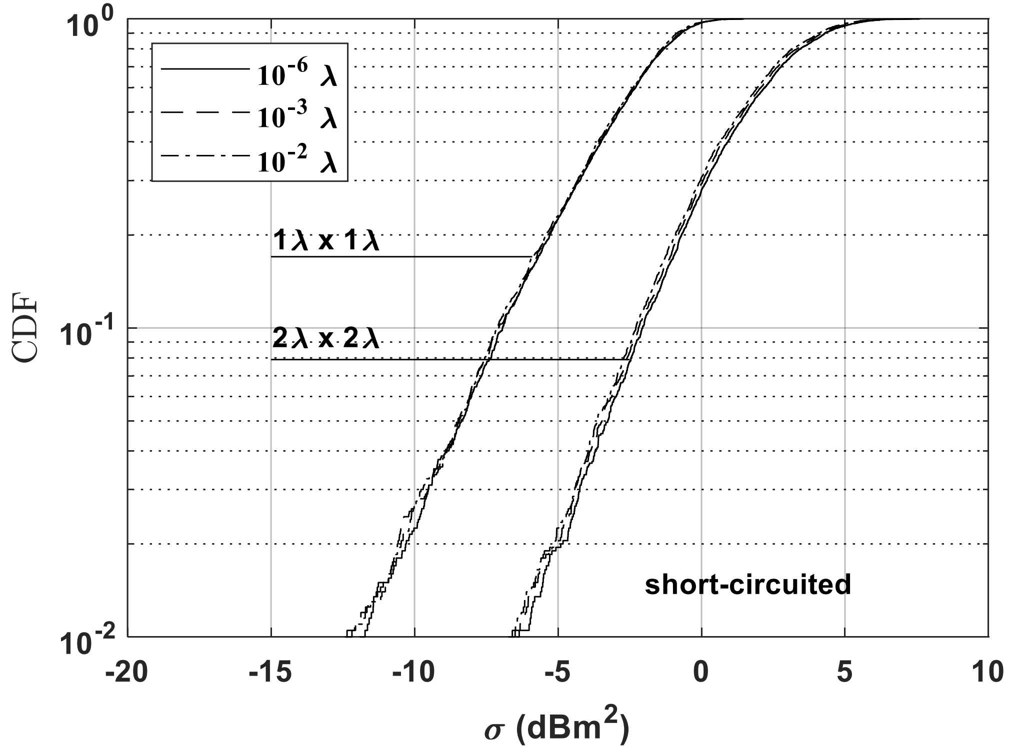
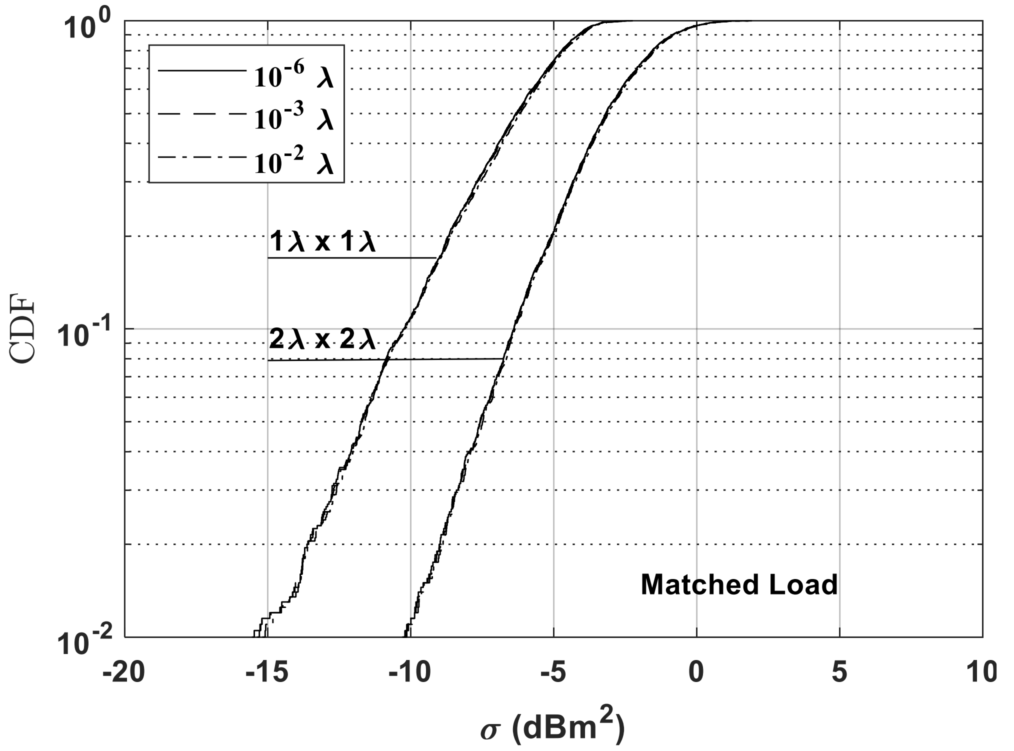
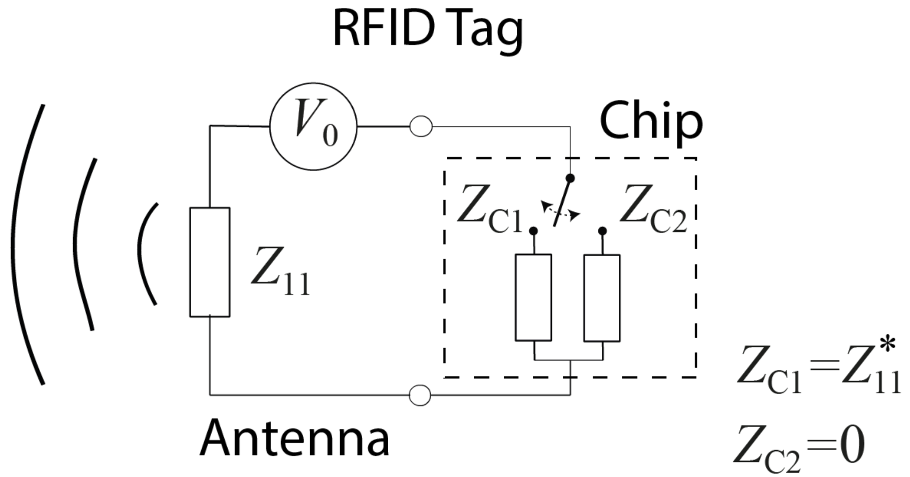
- Self impedance of different dipoles

$Z_{11-10^{-6}\lambda} = 76.6+j43.9$ $Z_{11-10^{-3}\lambda} = 83.7+j47.8$ $Z_{11-10^{-2}\lambda} = 102+j45.2$





ΔRCS – Simulation



- ΔRCS corresponds to the difference of two scalar RCS values when one dipole among others switches between two impedance states:

$$\Delta\sigma = |\sigma_1 - \sigma_2|$$

σ_1 : all dipoles in the set are matched.

σ_2 : one dipole in the set is short-circuited while others are matched.

Experimental design

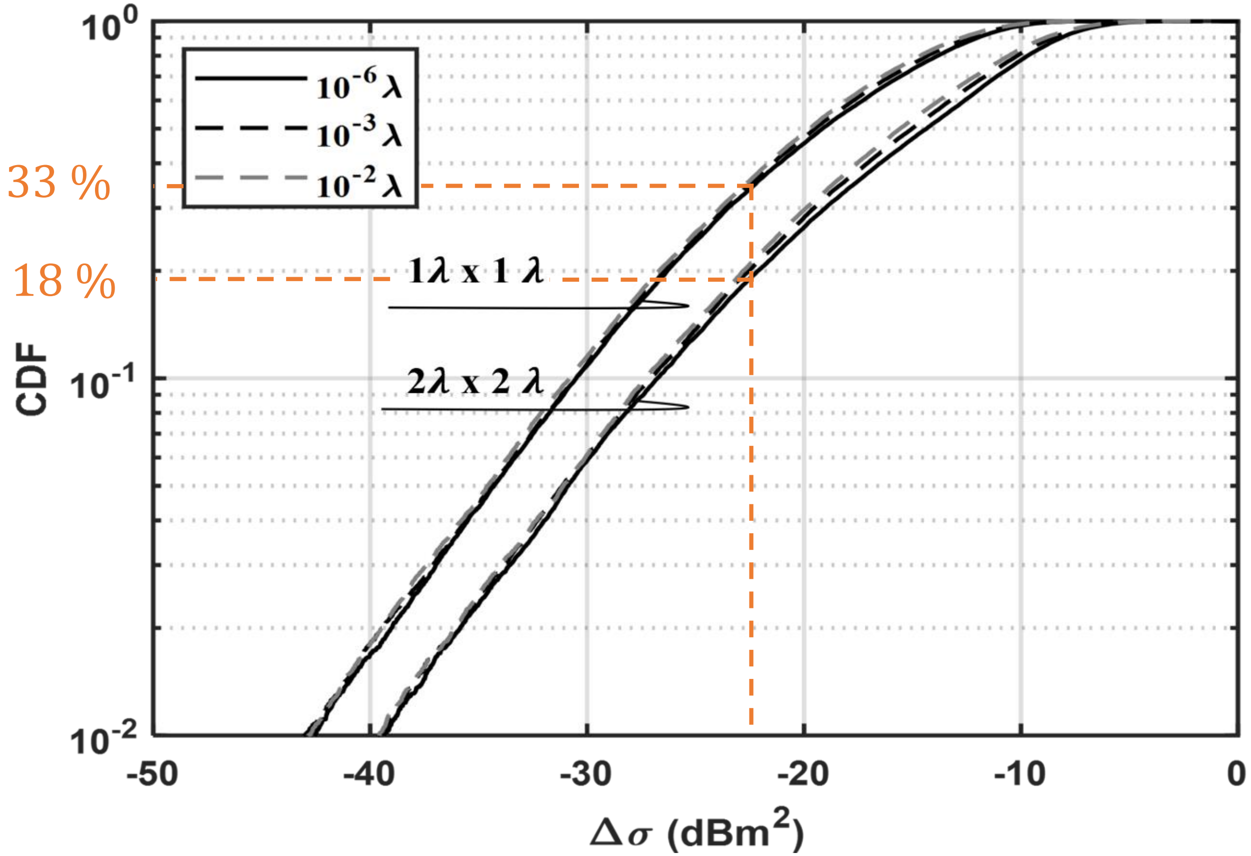
- Number of dipoles: 10
- Distribution area: $1\lambda x 1\lambda$, $2\lambda x 2\lambda$
- Number of trials: 2000
- Two simulations are made:
  - σ_1 : All 10 dipoles are matched ($Z_c = Z_{11}^*$) in each configuration.
  - σ_2 : 1 dipole is short-circuited ($Z_c = 0$) and 9 dipoles are matched ($Z_c = Z_{11}^*$).
- NEC
- Dipole diameter: $10^{-6}\lambda$, $10^{-3}\lambda$, $10^{-2}\lambda$
- Observation plane: ϕ_{E_i} = 0° , θ_{E_i} = 90°

ΔRCS analysis

- Define a ΔRCS threshold
- According to ISO/IEC 18000–6 (2013)

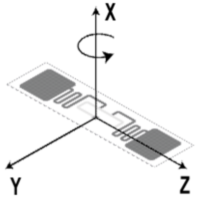
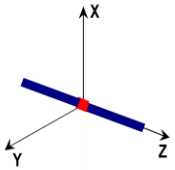
$$\Delta\sigma_{\text{th}} = 0.005\ \text{m}^2$$
$$= -23\ \text{dBm}^2$$

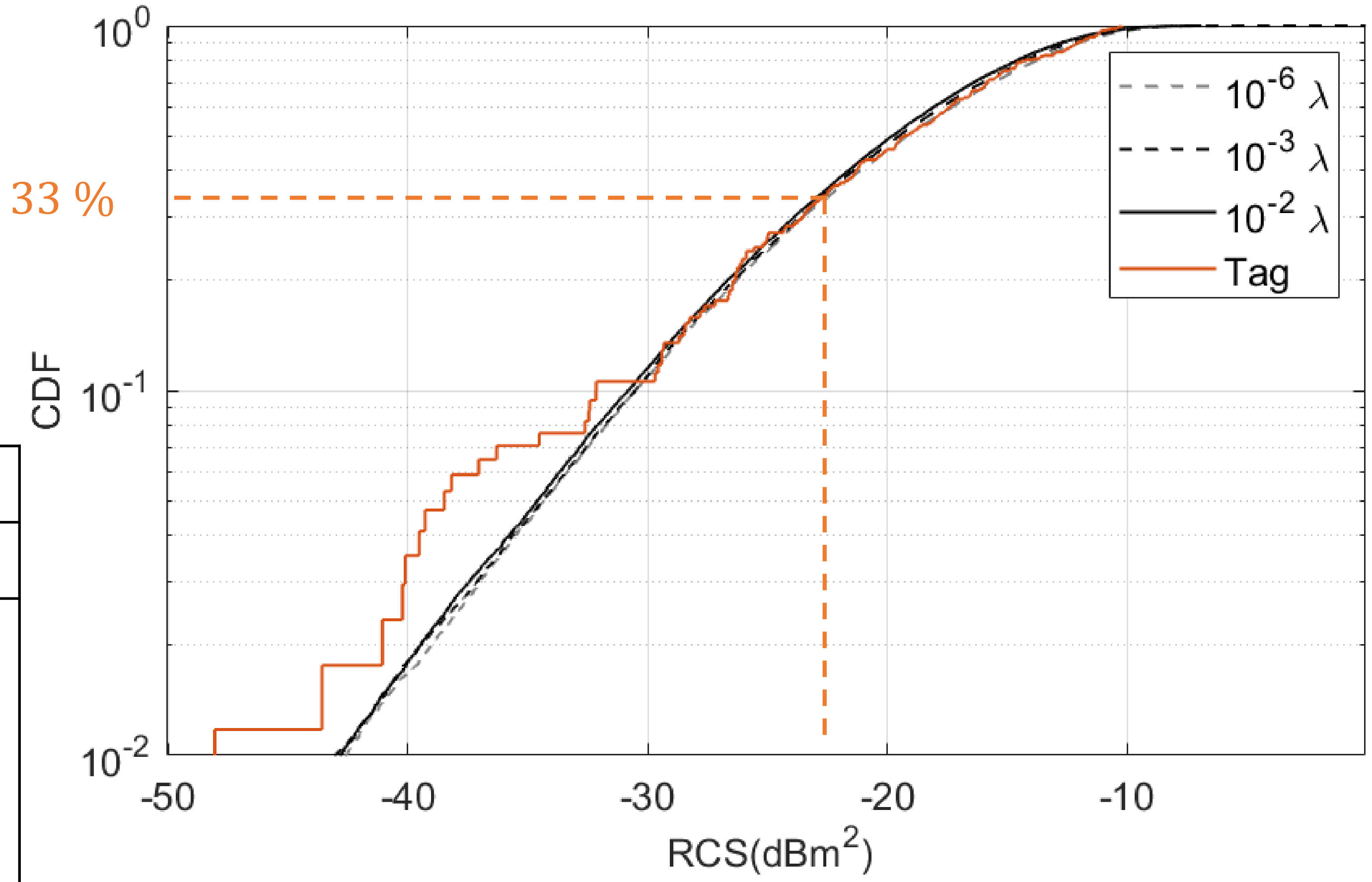
- $1\lambda \times 1\lambda$: 67% of the dipoles > $\Delta\sigma_{\text{th}}$
- $2\lambda \times 2\lambda$: 82% of the dipoles > $\Delta\sigma_{\text{th}}$



ΔRCS analysis – Tags

- Number of trials:
  - 2000 for dipoles
  - 17 for tags **(not enough data)**
- 1λ × 1λ
- 67% of the tags > $\Delta\sigma_{\mathrm{th}}$

Plane : ϕ = 90° and θ = 0°:5°:360°	
HFSS	NEC
• Simulation time for one tag : **3.30 hrs** 	• Simulation time for one dipole : **131 sec** 



Conclusion

- **Low cost asymptotic** estimation of the mutual coupling between **thin** dipoles (IEMF)
- **Low cost numerical** estimation of the mutual coupling between **thin** and **thick** dipoles (NEC)
- Statistical analysis of the **matching** and the **radiation** properties
- Towards a similar statistical group behaviour of thin dipoles, thick dipoles and **tag antennas**

Future work

- Dipole antennas vs. commercial tags
  - Measurement and statistical analysis
- Include uncertain environment
  - Electrical properties and scatterers
- Build a meta-model
  - PCE or other methods
- Statistical analysis of the system KPI
  - read-rate and read range