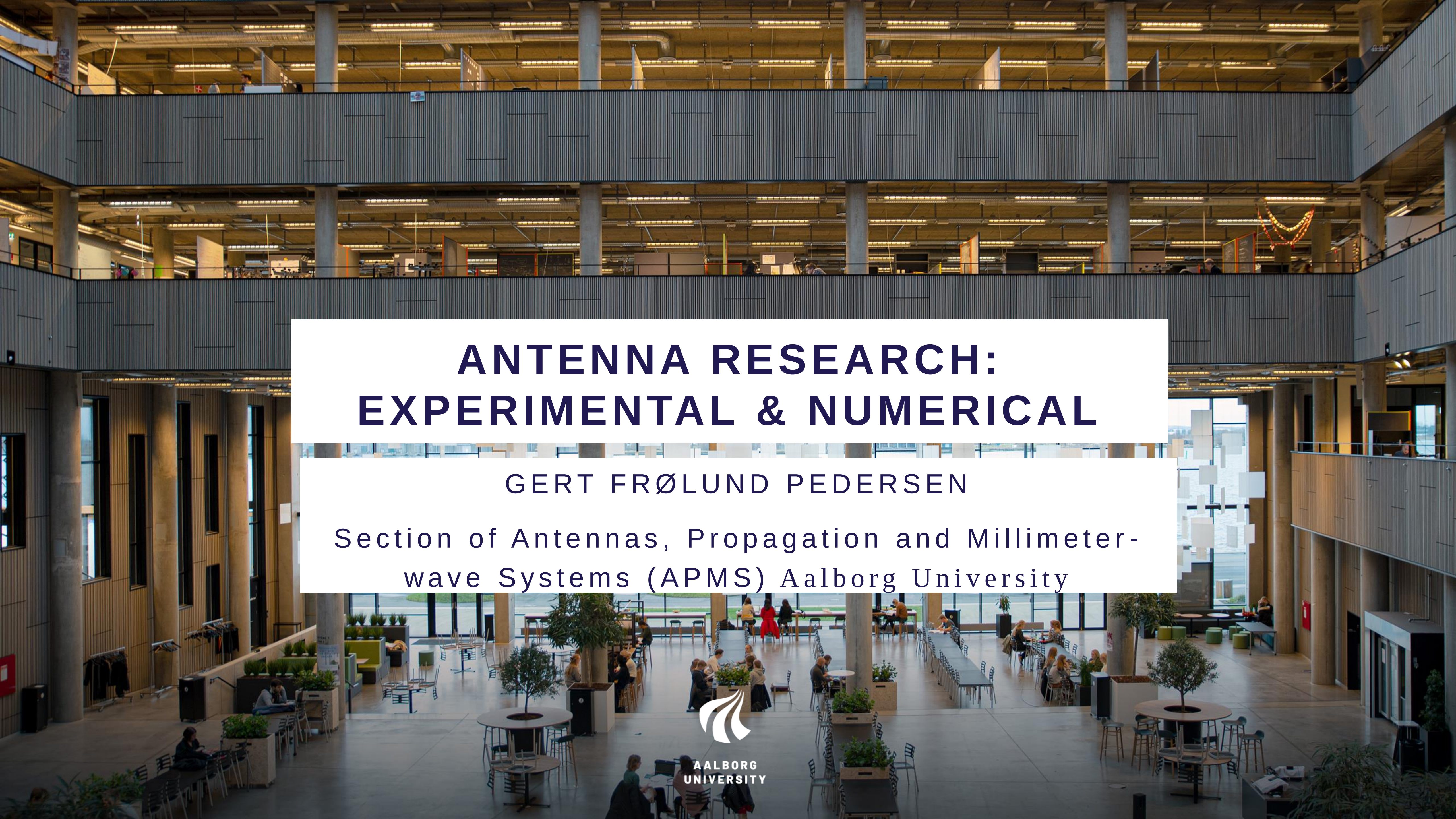
ANTENNA RESEARCH: EXPERIMENTAL & NUMERICAL

GERT FRØLUND PEDERSEN

Section of Antennas, Propagation and Millimeter-wave Systems (APMS) Aalborg University



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Outlines

Who am I

Antenna research at Aalborg University

Experimental facilities at Aalborg University

Numerical method

Numerical examples

Next evolution in Antennas

Background education/work

- Elektronikmekaniker Triax A/S,1987
- Bachelor E.E. Collage of Technology Dublin 1991
- Master E.E. Aalborg University 1993
- Researcher at Aalborg University since 1993 founding the antenna research for small terminals.

- Now professor with a large antenna group with 40+ full time researcher.
- World class antenna and radio LAB.
- Strong user of HPC.
- More than 500 international papers and 75 patents

Background research

The research has mainly been sponcered by the international and national industry – last years mainly larger innovation projects e.g.:

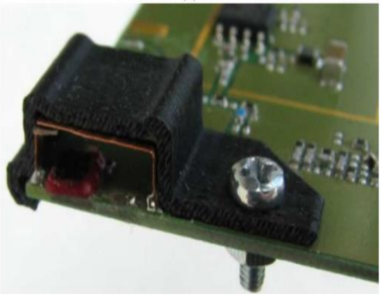
- 4GMCT (90 Mkr with Intel and Agilent)
- SAFE (48 Mkr with Wispry and Intel)
- iRotor (65 Mkr with LM-windpower, KK and polytech)
- Soft (8,7 Mkr with Gomspace and Reseiwe)
- RANGE (51 Mkr with Wispry and Sony)
- Virtuoso (110 Mkr with Intel, Telenor and Anite)
- MARS^2 (47 Mkr with Gomspace and Pridana-eletronik)

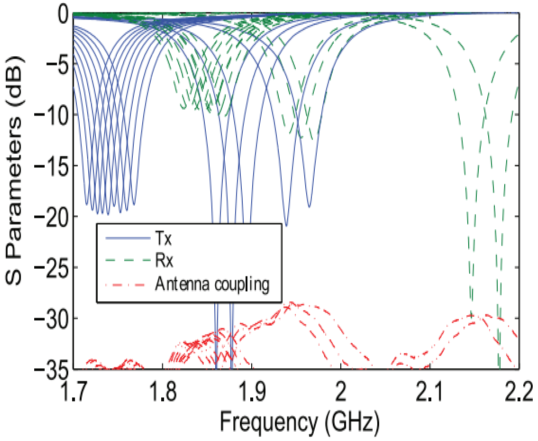
Small internal antennas development

1994 first Internal

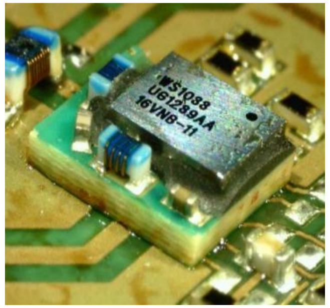
- Volume
- Bandwidth
- user

Tunable 2010

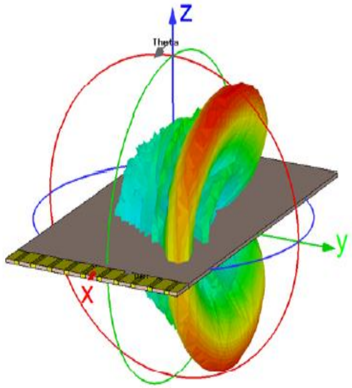


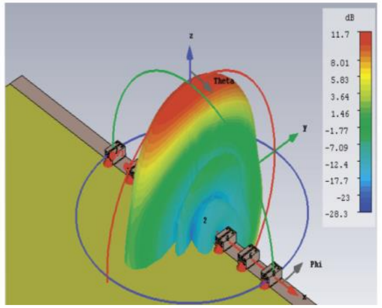


- MEMS
- Loss investigation
- Tuning range
- Integration with Tunable filters



MmWave 2015





- Phased array
- Antenna as component
- 3D Steering range

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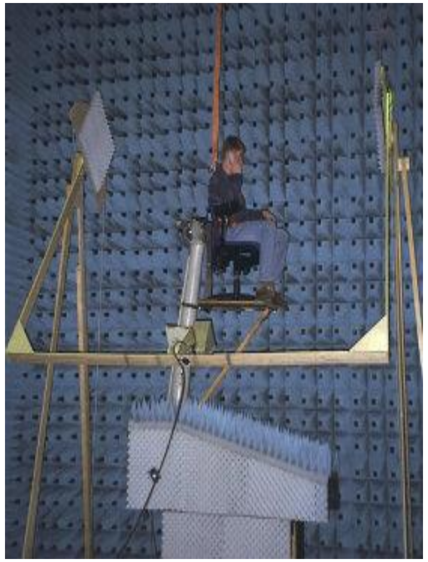
Study of small internal antennas

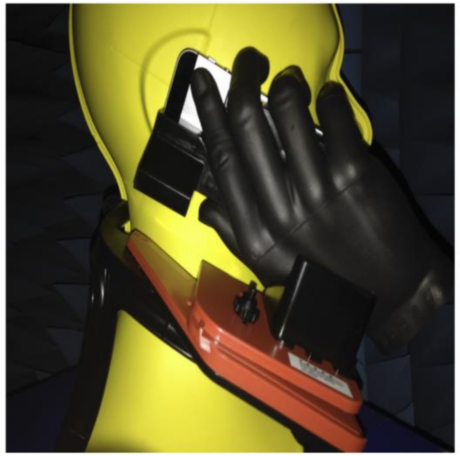
Pioneers of Over The Air (OTA) testing



Early investigations on Health - SAR

Grip studies

Standardized Testing of Multi-antenna commercial phones



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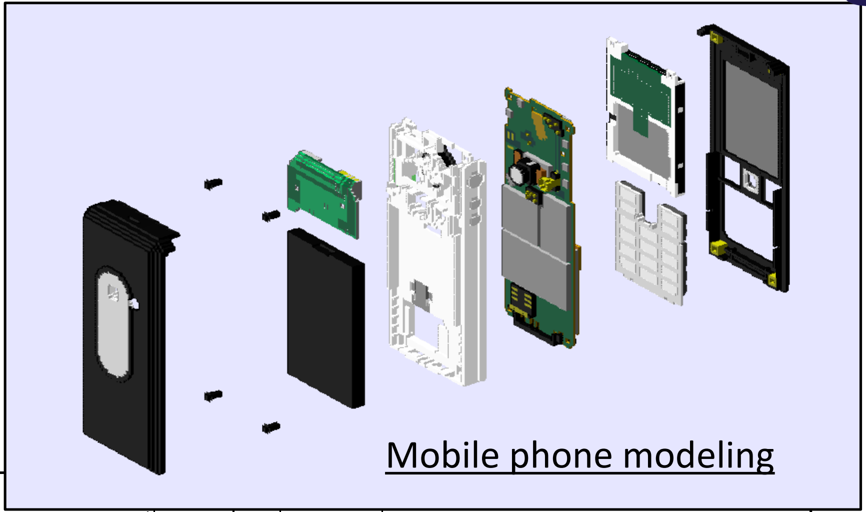
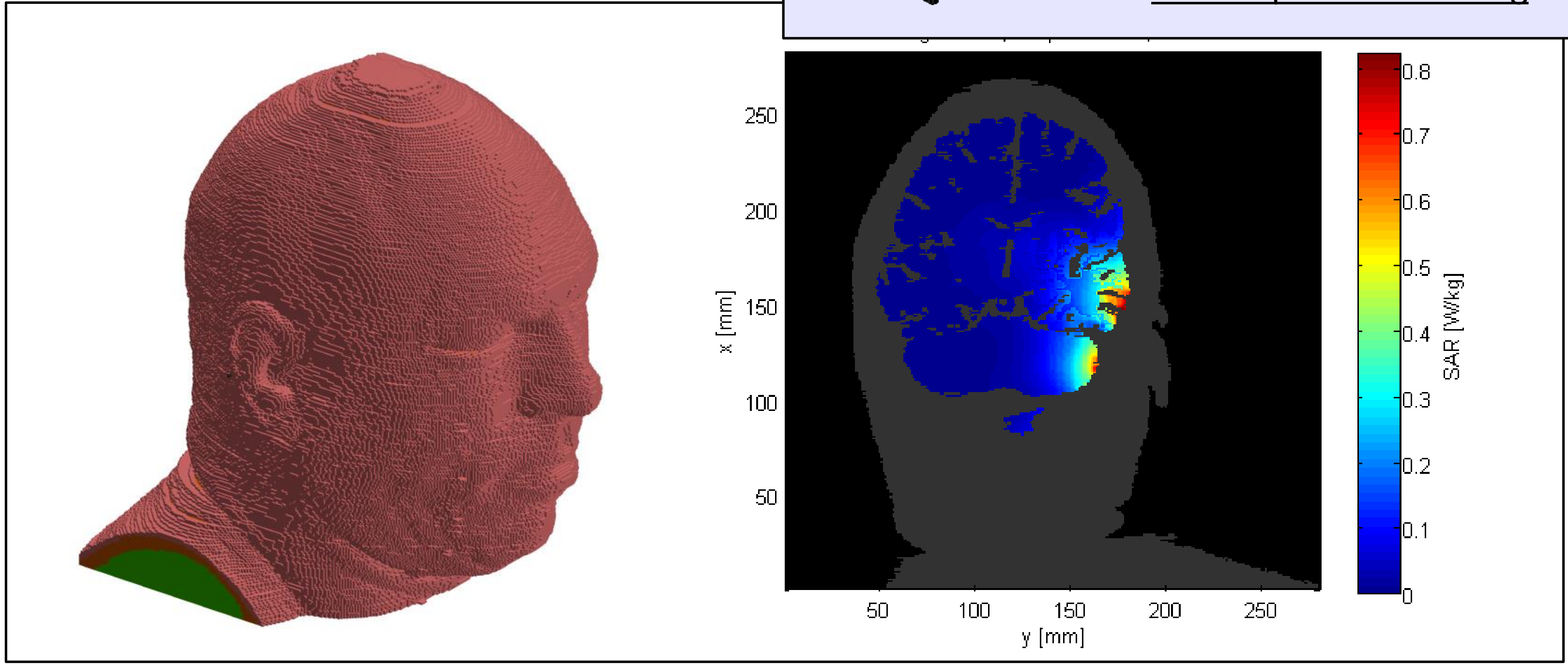
Electromagnetic Modeling

1. Proprietary FDTD solver
2. CST
3. HFSS



EM absorption in human tissues



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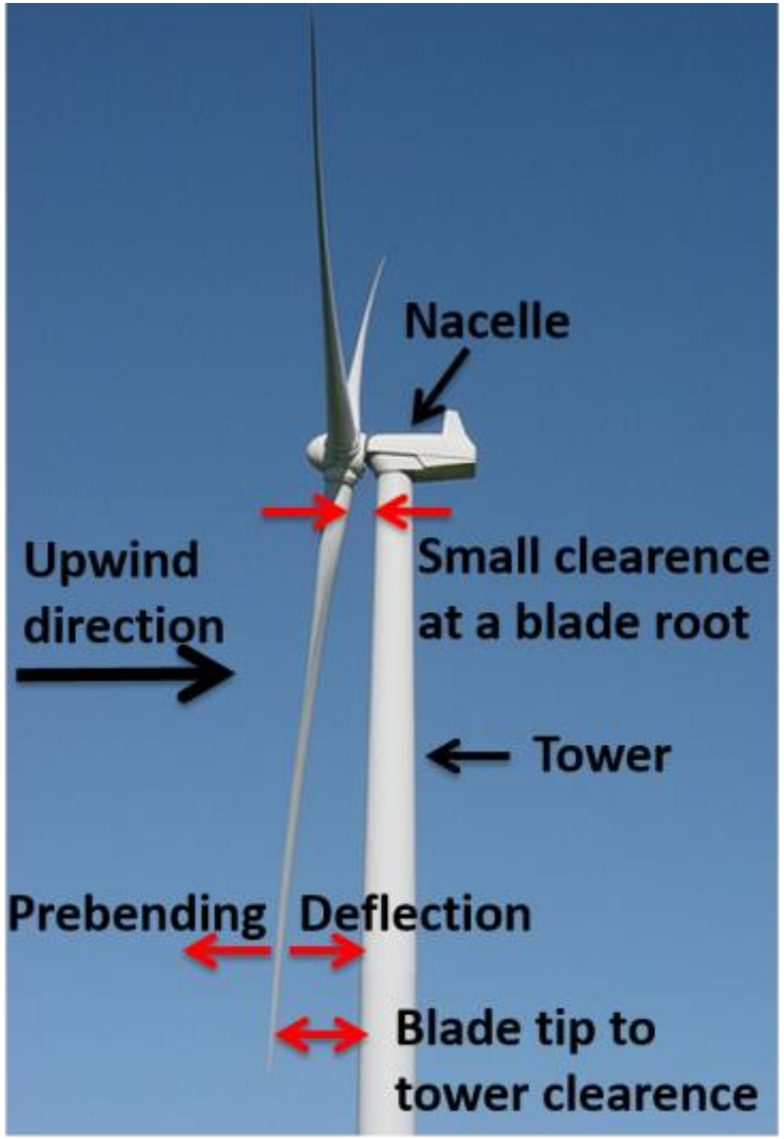
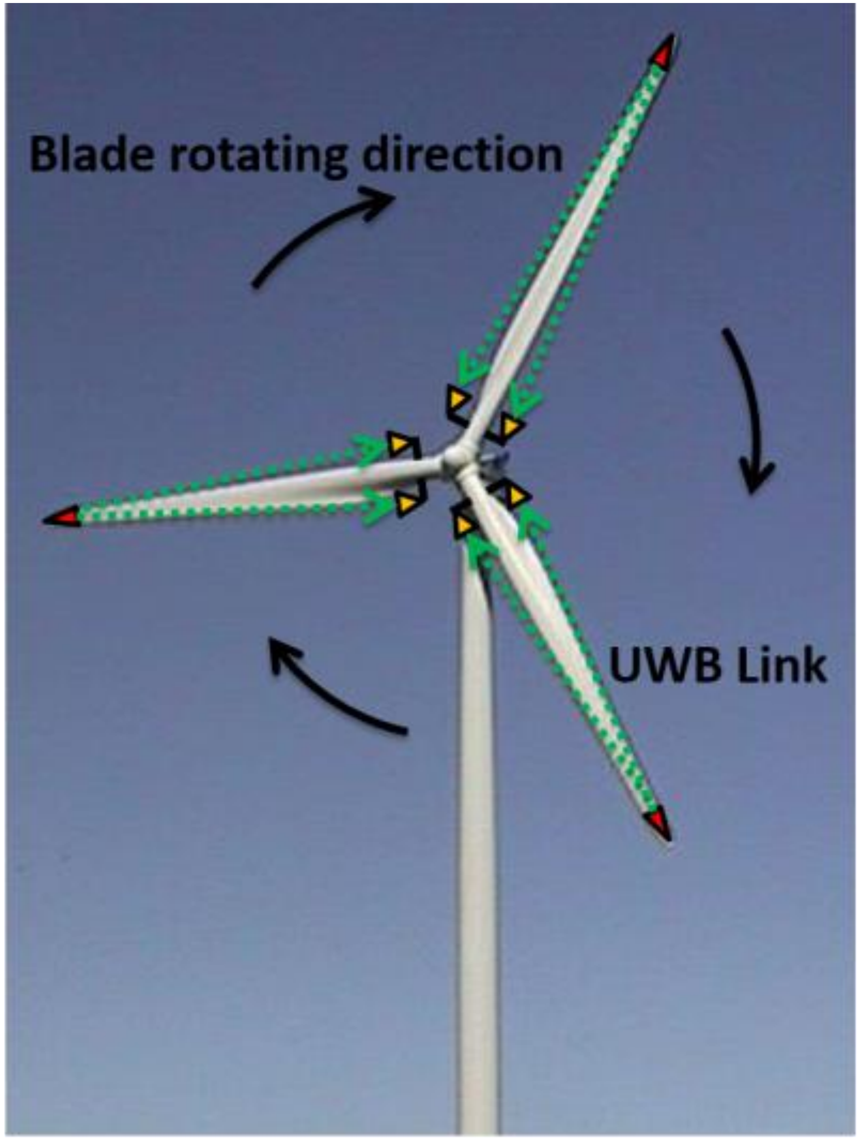
iRotor Project





Basestation site in Aalborg

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Phone and user

50 users on each floor.
2 antennas recorded simultaneously.
2 recordings for each person,
Extractable & Patch / Helix & Patch.
Each user walk on 4 by 2 meter path marked on the floor
Each user was asked to use the phone in a natural way.

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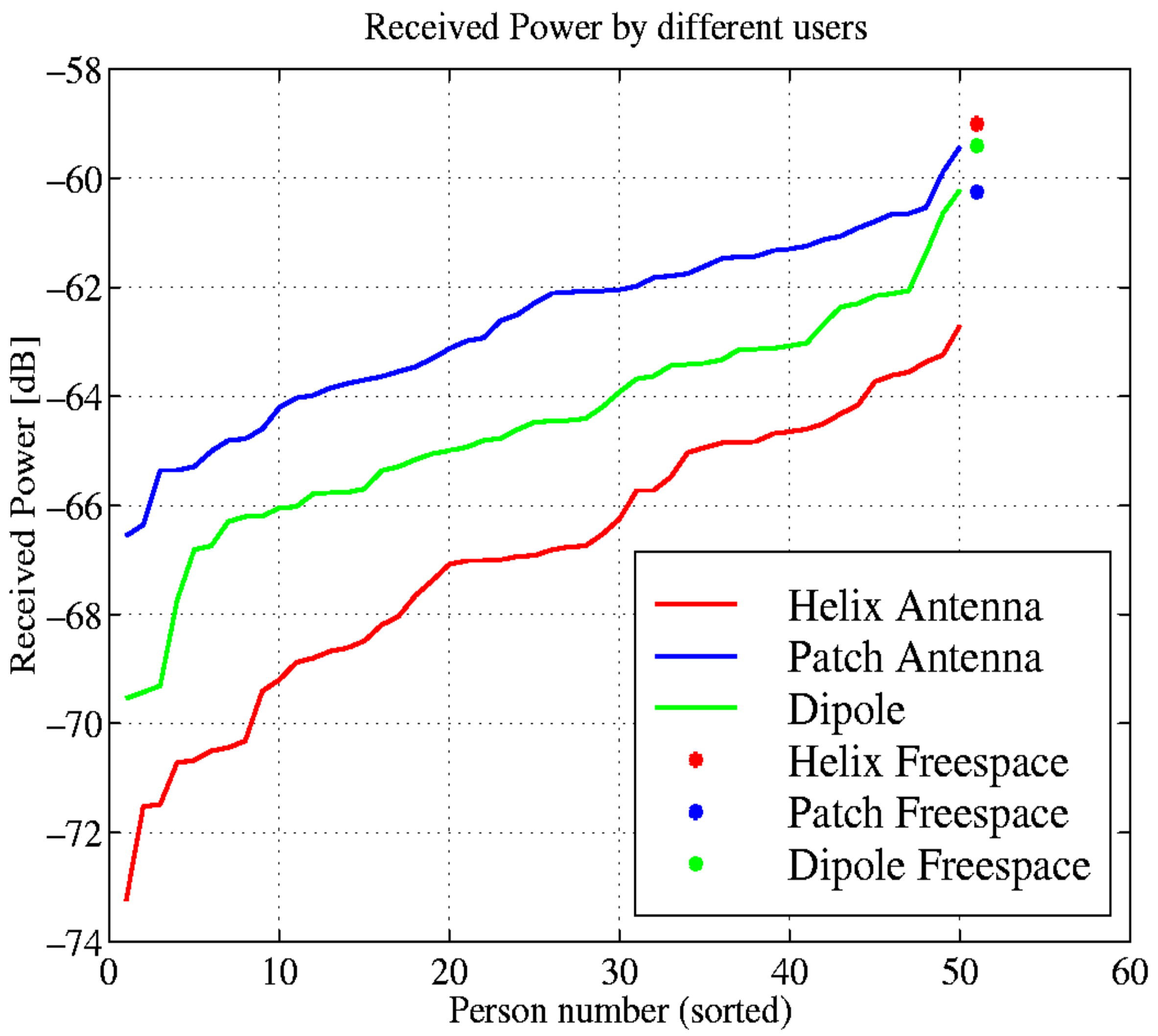
Received power, 50 users, 3 antennas



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Radiation measurements in anechoic room

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Summary on communication performance

- Very large variation among users.
- Absorption in the hand the largest problem.
- Large variation among phones (antennas).
- Good performance can be obtained if the antenna design gets special attention.

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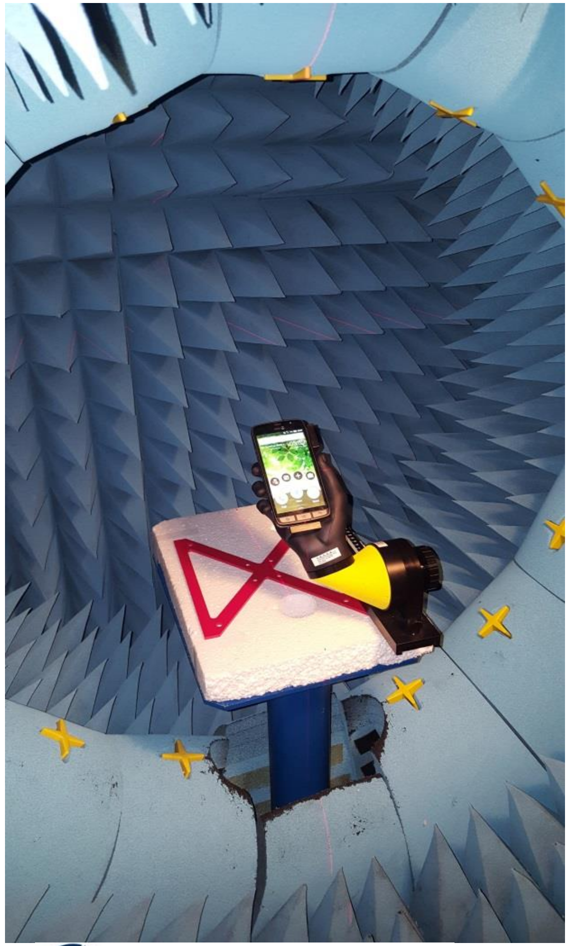
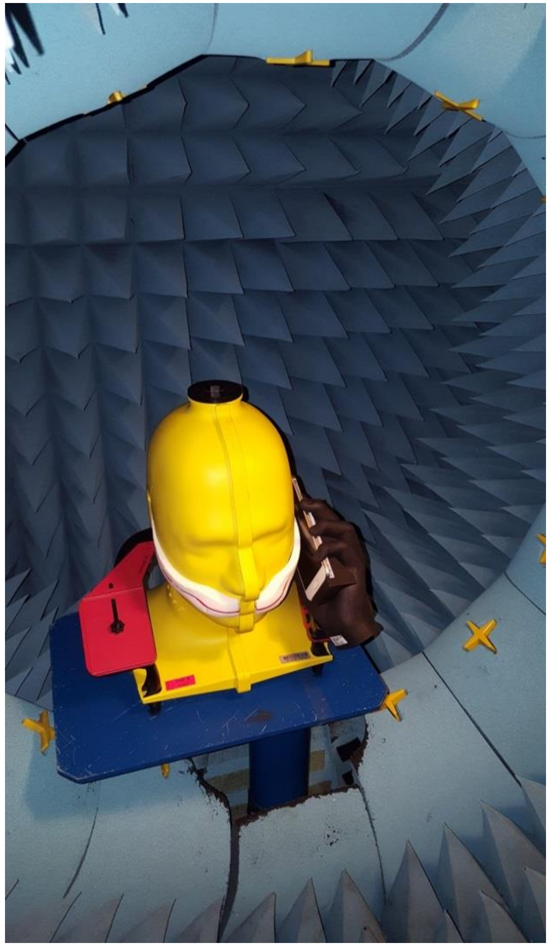
Mobile Phone Test

http://vbn.aau.dk/files/240065248/Mobile_Phone_Antenna_Performance_2016.pdf





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Danish Energy Agency

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Phones testede

Device	Phone Model
1	Apple iPhone 6
2	Apple iPhone 6S
3	Apple iPhone 6S Plus
4	Apple iPhone SE
5	Samsung Galaxy S7 Edge
6	Samsung Galaxy S7
7	Samsung Galaxy S6 Edge+
8	Samsung Galaxy S5 Mini
9	Samsung Galaxy J1
10	Sony Xperia Z3 Compact
11	Sony Xperia Z5
12	Sony Xperia Z5 Compact
13	LG G5

Device	Phone Model
14	Microsoft Lumia 640
15	Microsoft Lumia 650
16	Microsoft Lumia 950
17	Nexus 6P
18	Nexus 5X
19	Huawei P9
20	Huawei Honor 7
21	Huawei Y360
22	Xiaomi Mi5
23	HTC 10
24	HTC Desire 626
25	Doro Liberto 825
26	Doro PhoneEasy 530X

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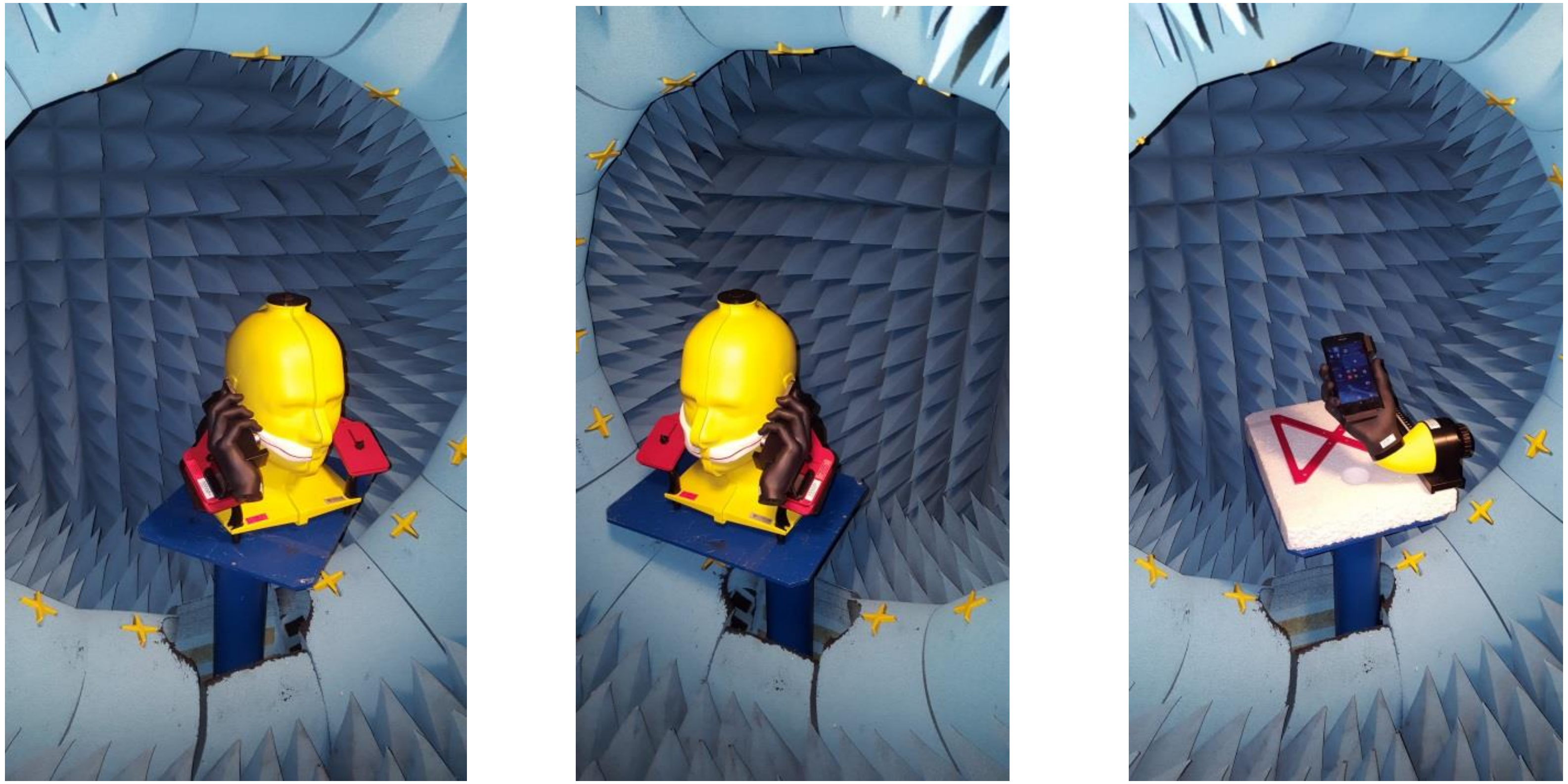
Voice Right and Left hand + Data



Setup for voice and data services including the specified phantom. All phantoms are as specified in the CTIA test plan [CTIA15] and made by Speag AG.

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Results Voice

Voice service Left hand (BHHL). TRP values, [dBm]					
Rank	Phone model	GSM 900	UMTS 900	GSM 1800	UMTS 2100
1	DORO PhoneEasy 530X	21,8	12,6	20,4	12,7
2	Microsoft Lumia 640	21,6	12,3	23,0	15,3
3	Microsoft Lumia 650	21,1	11,8	19,4	11,8
4	Sony Xperia Z3 Compact	21,0	12,2	18,2	12,1
5	Xiaomi Mi5	20,0	11,5	21,6	14,0
6	HTC Desire 626	19,8	9,2	17,7	11,1
7	Samsung Galaxy S7 Edge	19,6	9,0	20,3	14,8
8	Samsung Galaxy J1	19,3	9,2	20,1	11,5
9	Sony Xperia Z5 compact	19,3	10,8	19,4	12,8
10	Huawei Y360	19,2	10,2	19,4	11,8
11	Samsung Galaxy S5 mini	18,7	8,3	21,5	11,1
12	Sony Xperia Z5	18,3	9,4	20,6	14,7
13	HTC 10	18,2	5,6	17,4	7,0

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Results Voice continued

Voice service Left hand (BHHL). TRP values, [dBm]					
Rank	Phone model	GSM 900	UMTS 900	GSM 1800	UMTS 2100
14	Samsung Galaxy S6 Edge+	18,1	10,9	18,0	14,3
15	DORO Liberto 825	18,0	9,6	18,5	10,6
16	Nexus 6P	17,2	8,3	17,3	8,8
17	Huawei Honor 7	16,0	7,6	20,5	12,7
18	Samsung Galaxy S7	15,5	11,2	19,0	15,6
19	Microsoft Lumia 950	15,3	8,8	19,5	12,9
20	Huawei P9	15,0	8,2	19,0	11,6
21	Nexus 5X	14,5	6,8	20,8	13,1
22	LG G5	12,2	2,5	17,9	6,0
23	Apple iPhone SE	12,1	3,3	18,1	3,6
24	Apple iPhone 6	10,1	7,4	18,0	8,4
25	Apple iPhone 6S	8,7	-0,6	17,9	10,4
26	Apple iPhone 6S plus	6,5	-2,3	18,6	7,5

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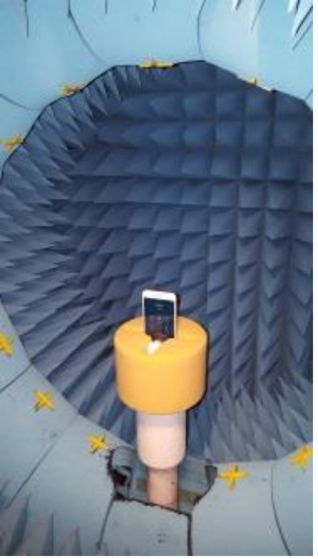

Results user vs no user

Free space vs Voice service for GSM900 phones. TRP [dBm]			
Model	Free space	BHHR	BHHL
iPhone S6+	26,9	18,7	6,5
Huawei P9	27,0	8,3	15,0
Doro Phone Easy 530x	28,4	20,1	21,8
HTC Desire 626	30,9	22,5	19,8

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EXPERIMENTAL FACILITIES

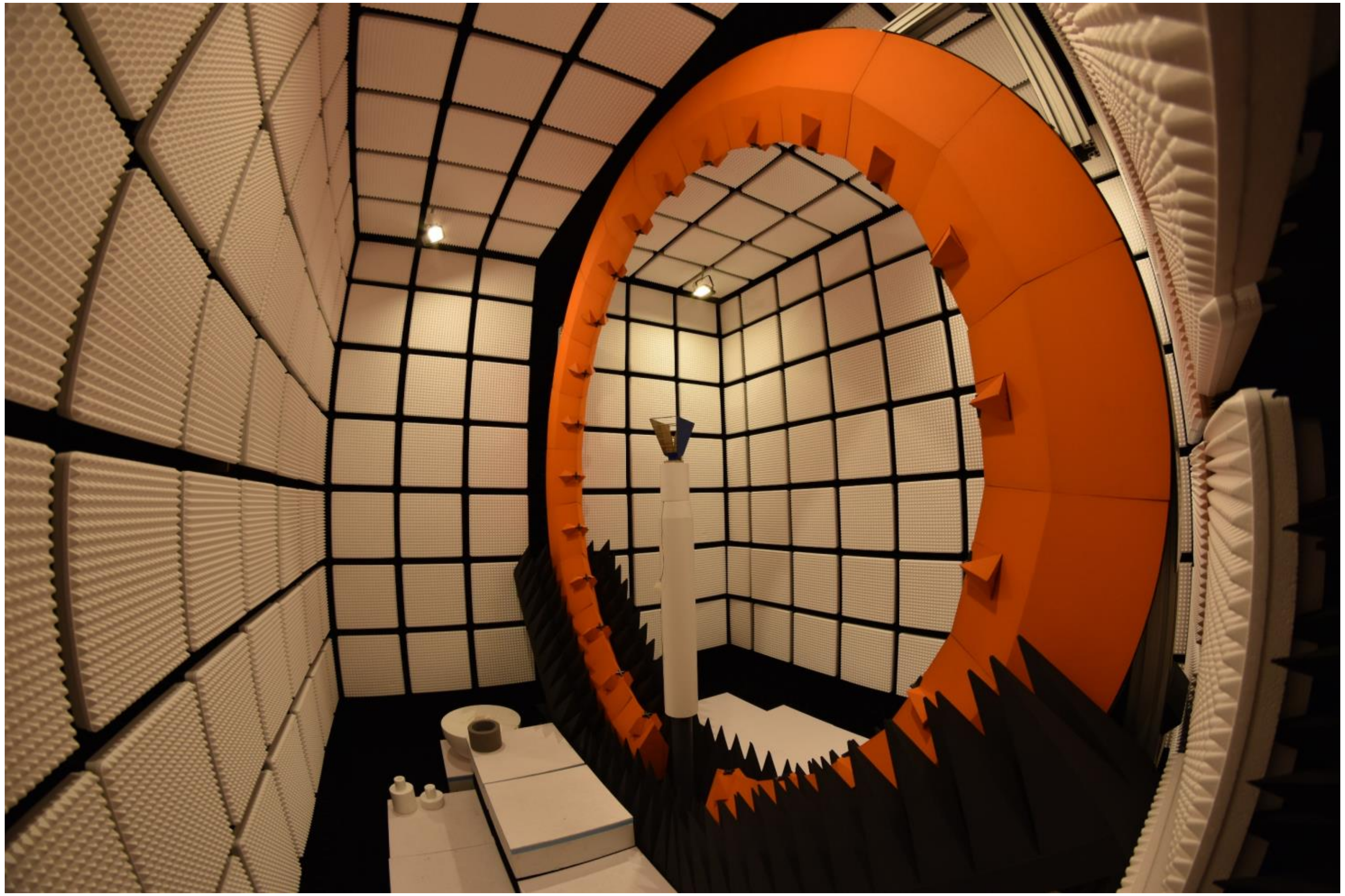
- Large Anechoic Room
- Small Anechoic Room
- Compact Range
- Radio Propagation Lab

Large Anechoic Room

- Size: 10 x 10 x 14 meters
- Equipped with two measurement systems:
  - A roll over azimuth range (9,5m distance)
    - Capable of carrying 150 kg
    - Near field and far field measurements up to 110 GHz
    - Using a laser tracker to increase accuracy
  - Gantry arm system (3 m distance, 6 meter in diameter)
    - Near field measurements up to 40 GHz
    - Far field up to 110 GHz
    - For small devices and persons
    - Large equipment up to 3500 kg (e.g. a car)
    - Using a laser tracker to increase accuracy

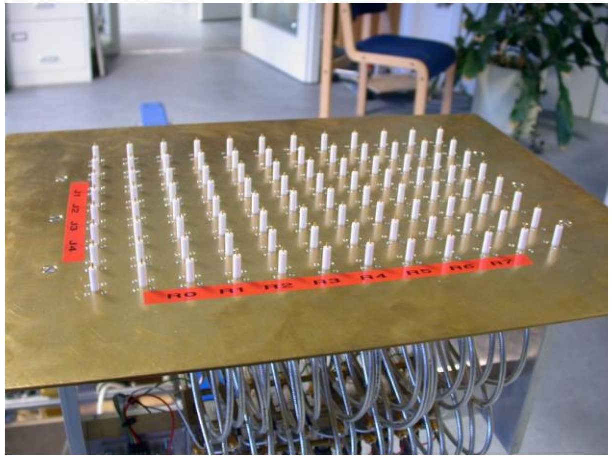
Small Anechoic Room

- Size: 5 x 5 x 5 meters
- Equipped with SATIMO StarGate 24
- The systems cover the frequency range from 400 MHz to 6 GHz
- Near field antenna measurements
- OTA testing with systems like GSM, UMTS, LTE, WIFI, and Bluetooth
- Capable of carrying 100 kg
- Test with persons is possible
- Head and hand phantoms for mobile testing



MIMO Measurements

- Massive MIMO measurements up to 6 GHz
- 16 x 8 fully parallel channels
- 2 x 16 MIMO up to 40 GHz



Measurement Campaigns

FDTD Method in 3 Dimensions

Maxwell's equations decomposed into components – **6 equations for 6 field components.**

$$\nabla \times \mathbf{H} = \mathbf{J} + \epsilon \frac{\partial \mathbf{E}}{\partial t} \longrightarrow$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon}\left[\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - (J_{x,\text{source}} + \sigma E_x)\right]$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\epsilon}\left[\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - (J_{y,\text{source}} + \sigma E_y)\right]$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\epsilon}\left[\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - (J_{z,\text{source}} + \sigma E_z)\right]$$

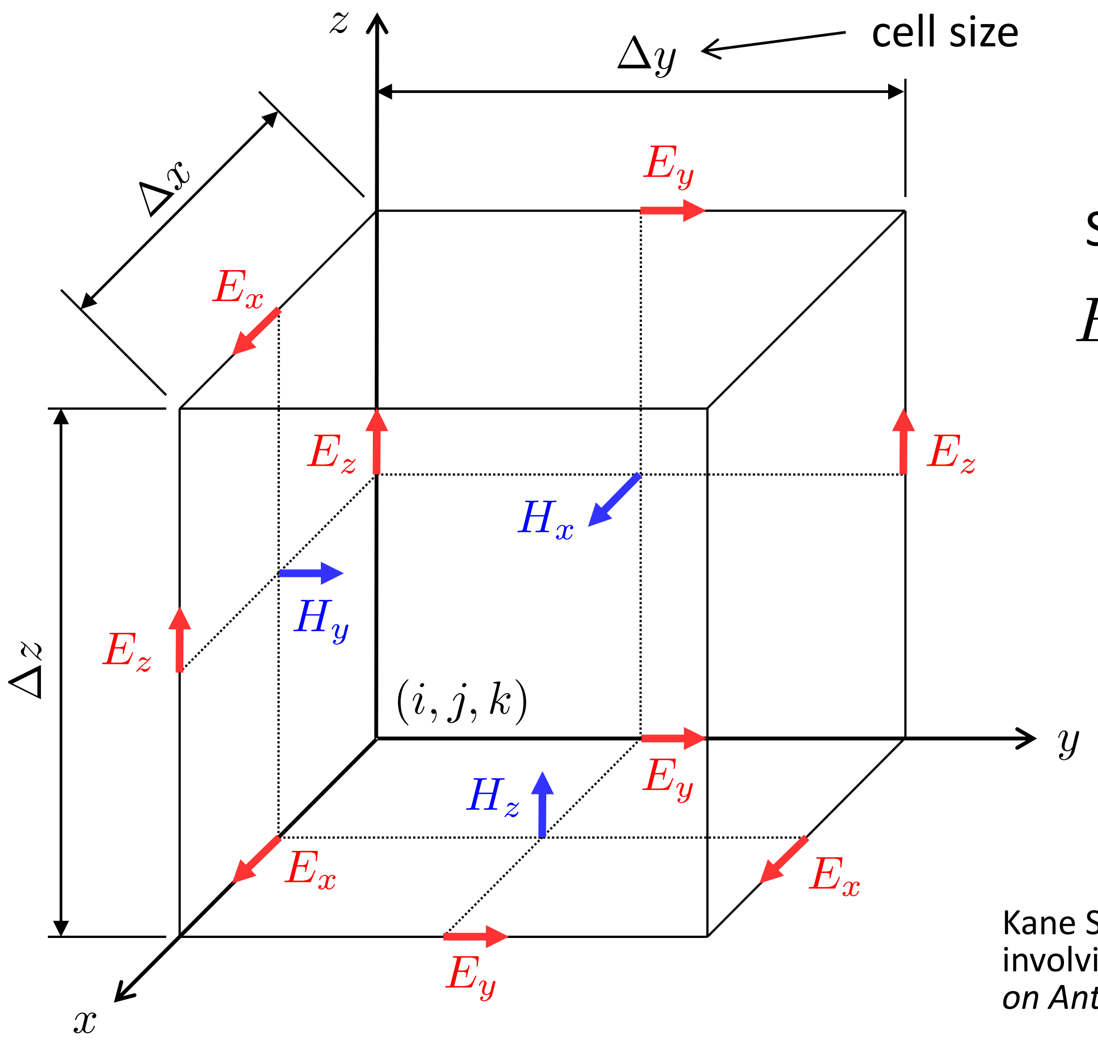
$$-\nabla \times \mathbf{E} = \mathbf{M} + \mu \frac{\partial \mathbf{H}}{\partial t} \longrightarrow$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - (M_{x,\text{source}} + \sigma^* H_x)\right]$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - (M_{y,\text{source}} + \sigma^* H_y)\right]$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - (M_{z,\text{source}} + \sigma^* H_z)\right]$$

Yee Cell



Coordinates: $t_n = n\Delta t$ $\quad x_i = i\Delta x$ $\quad y_j = j\Delta y$ $\quad z_k = k\Delta z$

Shorthand notation:

$$E_x(x_i, y_j, z_k, t_n) = E_x\Big|_{i,j,k}^{n}$$

time coordinate (n)

space coordinates (i,j,k)

The field samples are staggered in space and in time to facilitate the use of finite differences.

Kane S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media." *IEEE Transactions on Antennas and Propagation*. Vol. 14, No. 3, 1966, pp. 302–307.

Yee Difference Scheme

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - (M_{x,\text{source}} + \sigma^* H_x)\right]$$

finite differences

$$\frac{H_x|_{i,j+0.5,k+0.5}^{n+0.5} - H_x|_{i,j+0.5,k+0.5}^{n-0.5}}{\Delta t}$$

$$\frac{E_y|_{i,j+0.5,k+1}^{n} - E_y|_{i,j+0.5,k}^{n}}{\Delta z}$$

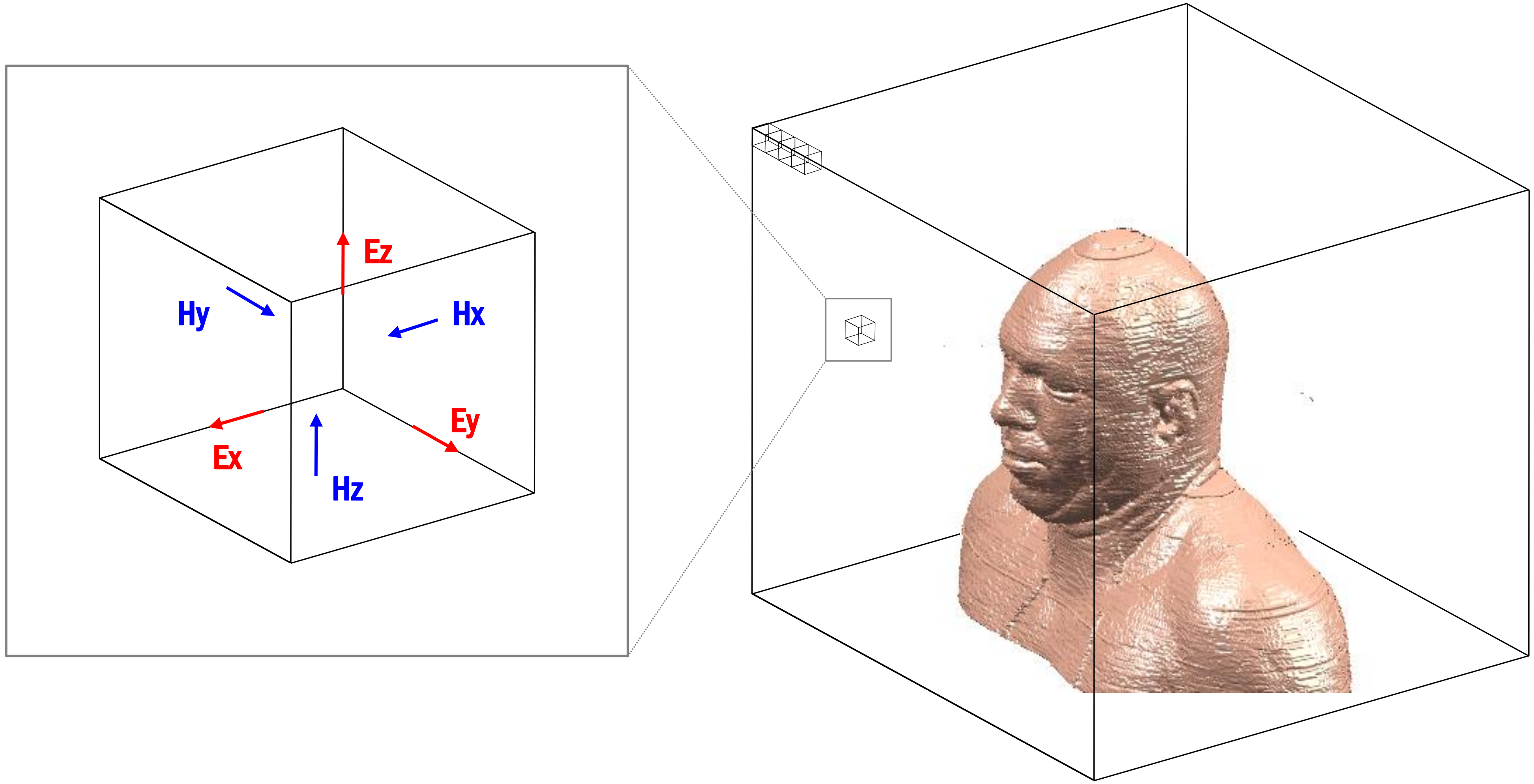
$$\frac{E_z|_{i,j+1,k+0.5}^{n} - E_z|_{i,j,k+0.5}^{n}}{\Delta y}$$

average

$$\frac{H_x|_{i,j+0.5,k+0.5}^{n+0.5} + H_x|_{i,j+0.5,k+0.5}^{n-0.5}}{2}$$

$$H_x|_{i,j+0.5,k+0.5}^{n+0.5} = D_\text{a}|_{i,j+0.5,k+0.5} H_x|_{i,j+0.5,k+0.5}^{n-0.5} + D_\text{b}|_{i,j+0.5,k+0.5} \times \left(\frac{E_y|_{i,j+0.5,k+1}^{n} - E_y|_{i,j+0.5,k}^{n}}{\Delta z} - \frac{E_z|_{i,j+1,k+0.5}^{n} - E_z|_{i,j,k+0.5}^{n}}{\Delta y} - M_{x,\text{source}}|_{i,j+0.5,k+0.5}^{n}\right)$$

Yee Cells and the Computational Domain



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FDTD Stability Condition in 3D

$$c\Delta t\sqrt{\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}+\frac{1}{(\Delta z)^2}}\leq 1$$

Numerical stability factor
(Courant number)

If $\Delta = \Delta x = \Delta y = \Delta z$ then

$$\frac{c\Delta t}{\Delta}\leq\frac{1}{\sqrt{3}}$$

… for 3D FDTD

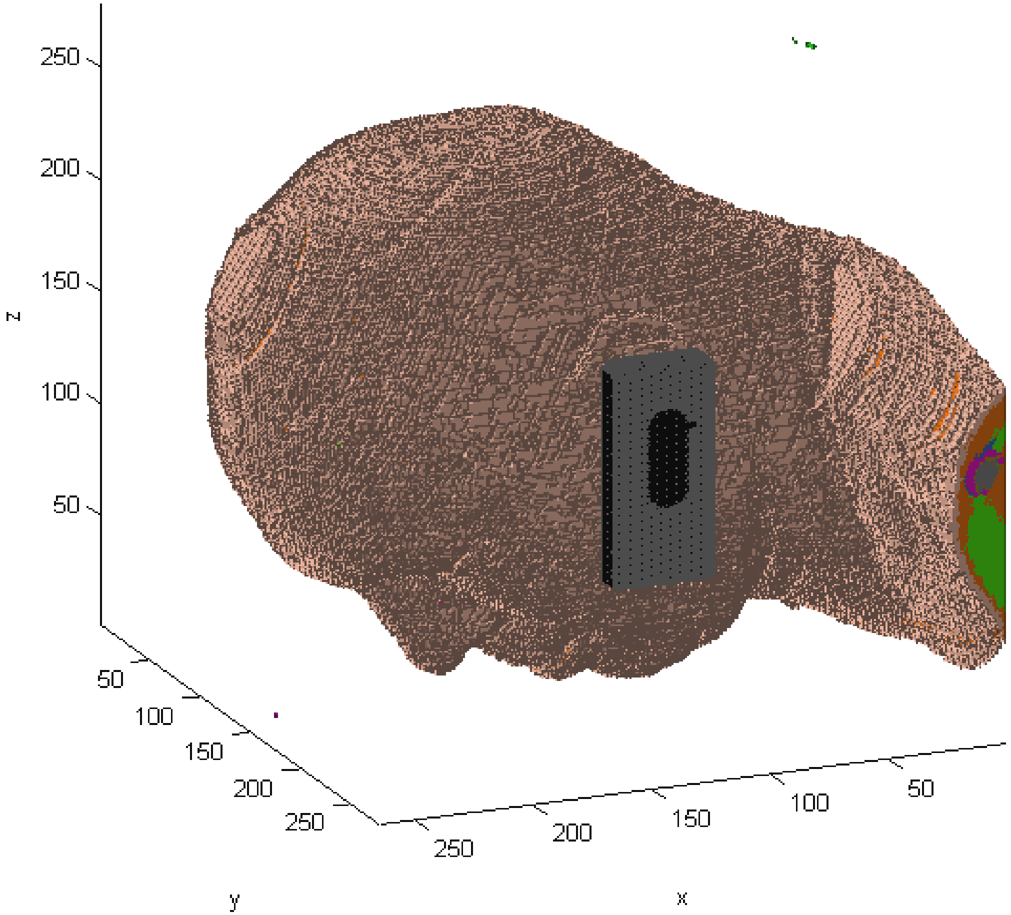
Courant-Friedrichs-Lewy (CFL) stability condition

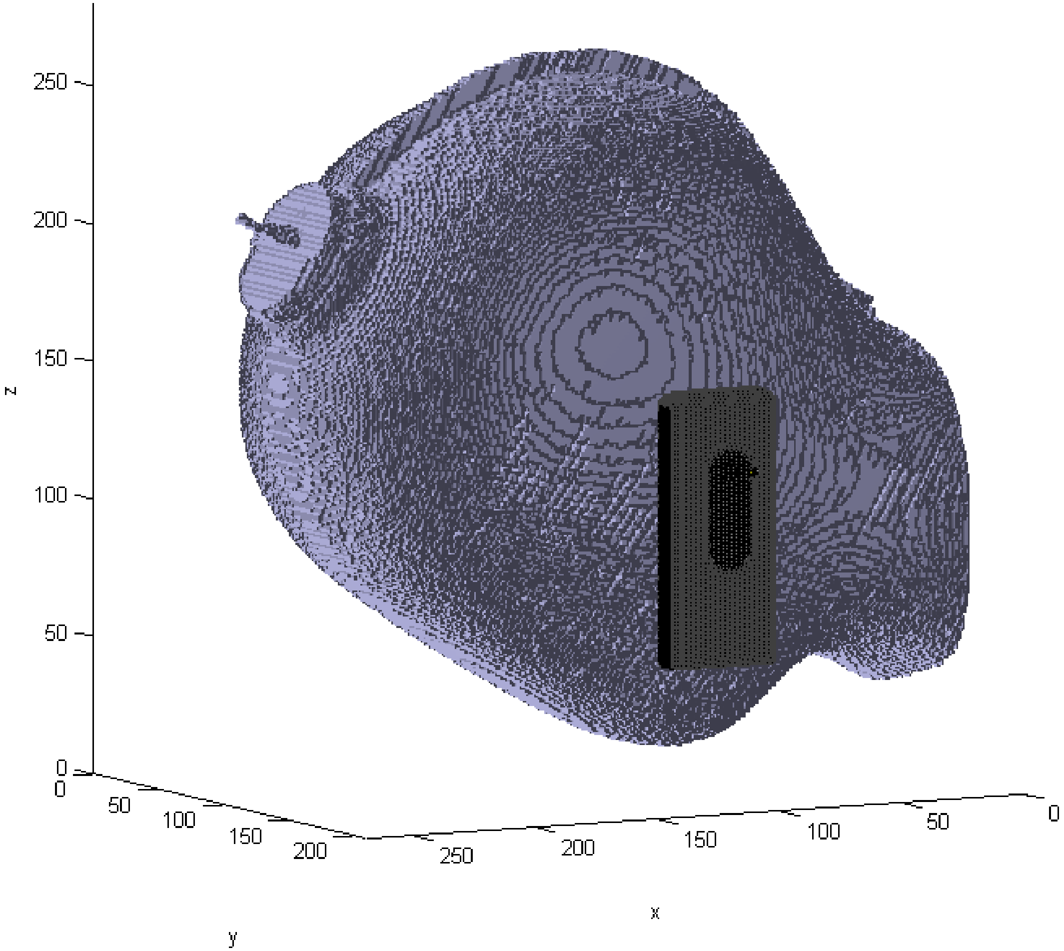
AAU FDTD code on HPC

Fyrkat (2008)	Abacus (2015)	LUMI-C (2021)
• 24 nodes * 144 GB RAM • 12 cores each • **3.5 TB RAM total**	• Slim: 448 nodes * 64 GB RAM • Fat: 64 nodes * 512 GB RAM • 2x12 cores each • **32 TB RAM total** (on fat)	• Type 1: 1376 nodes * 256 GB RAM • Type 2: 128 nodes * 512 GB RAM • Type 3: 32 nodes * 1024 GB RAM • 2x64 cores each • **352 TB RAM total** (on type 1)

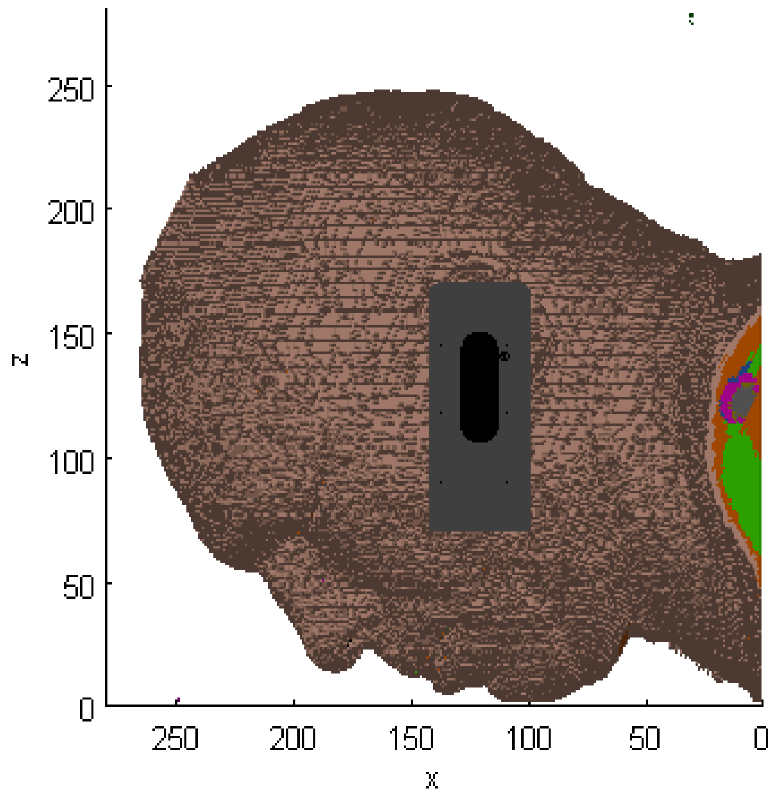
RAM scaling: 1x ~10x ~100x

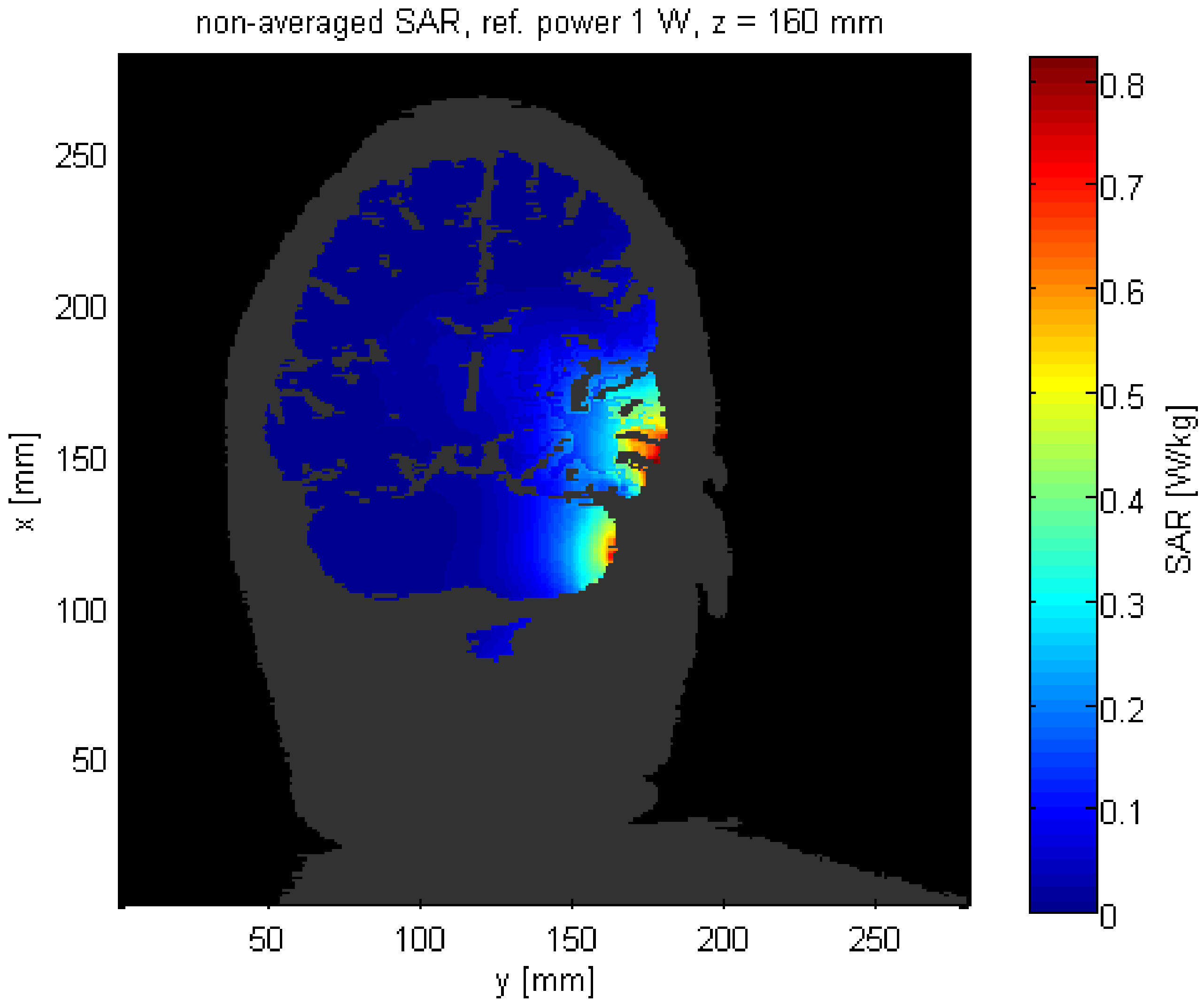
Simulation example: Human phantoms with a mobile phone

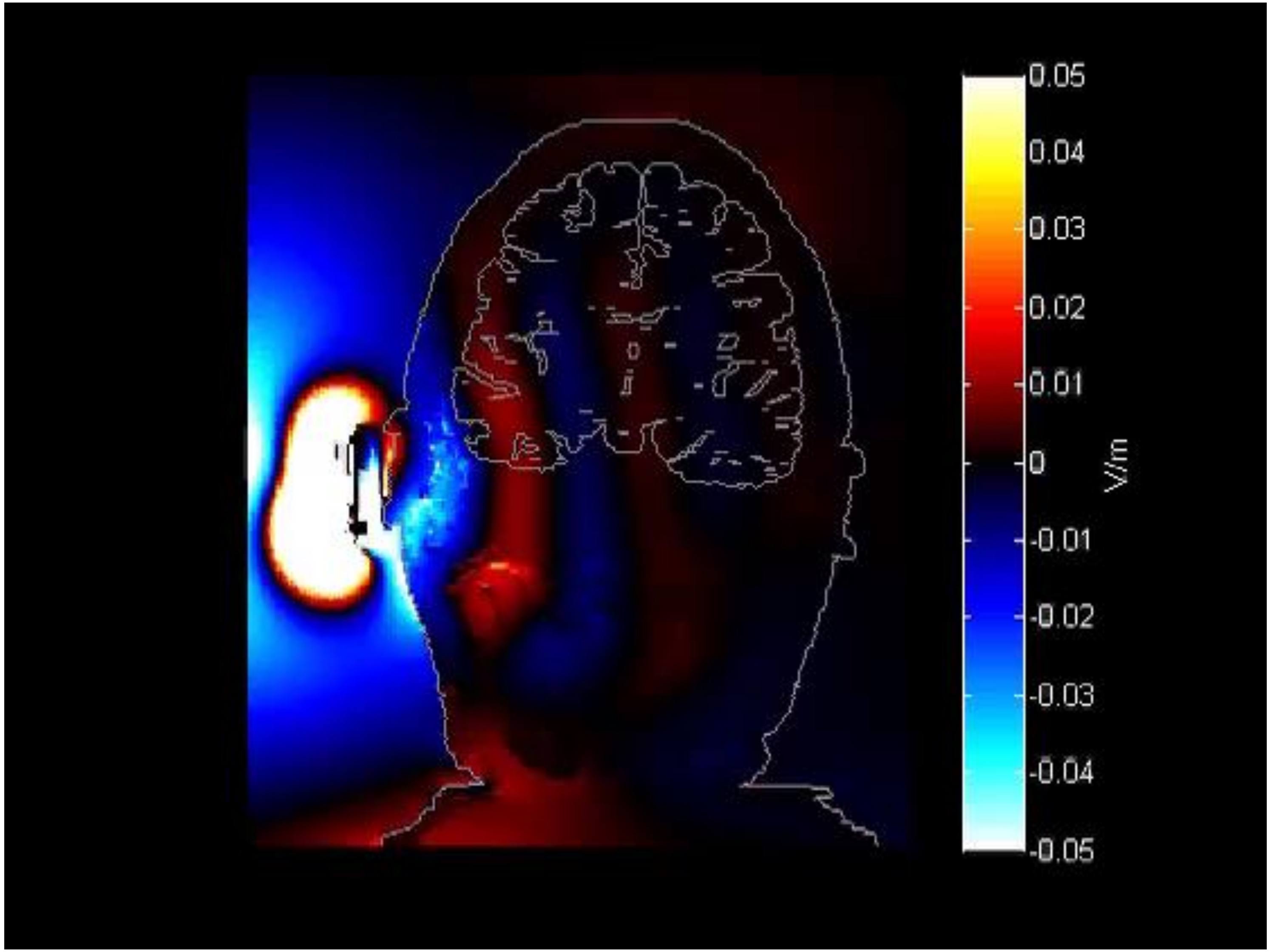




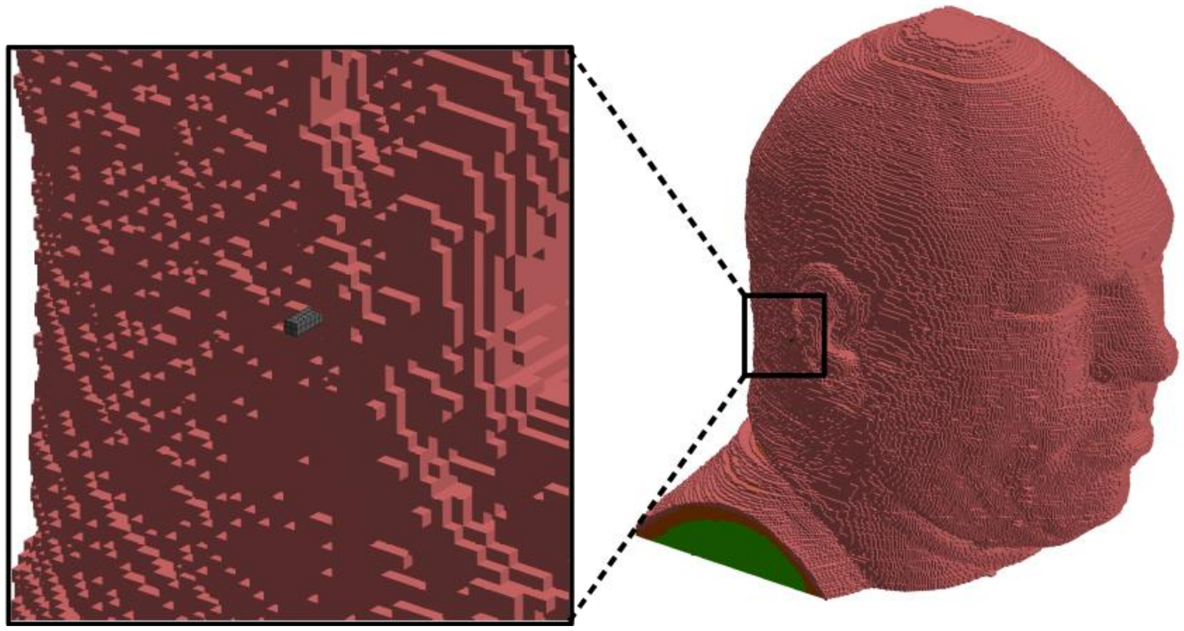
Simulation example: SAR distribution in brain tissues



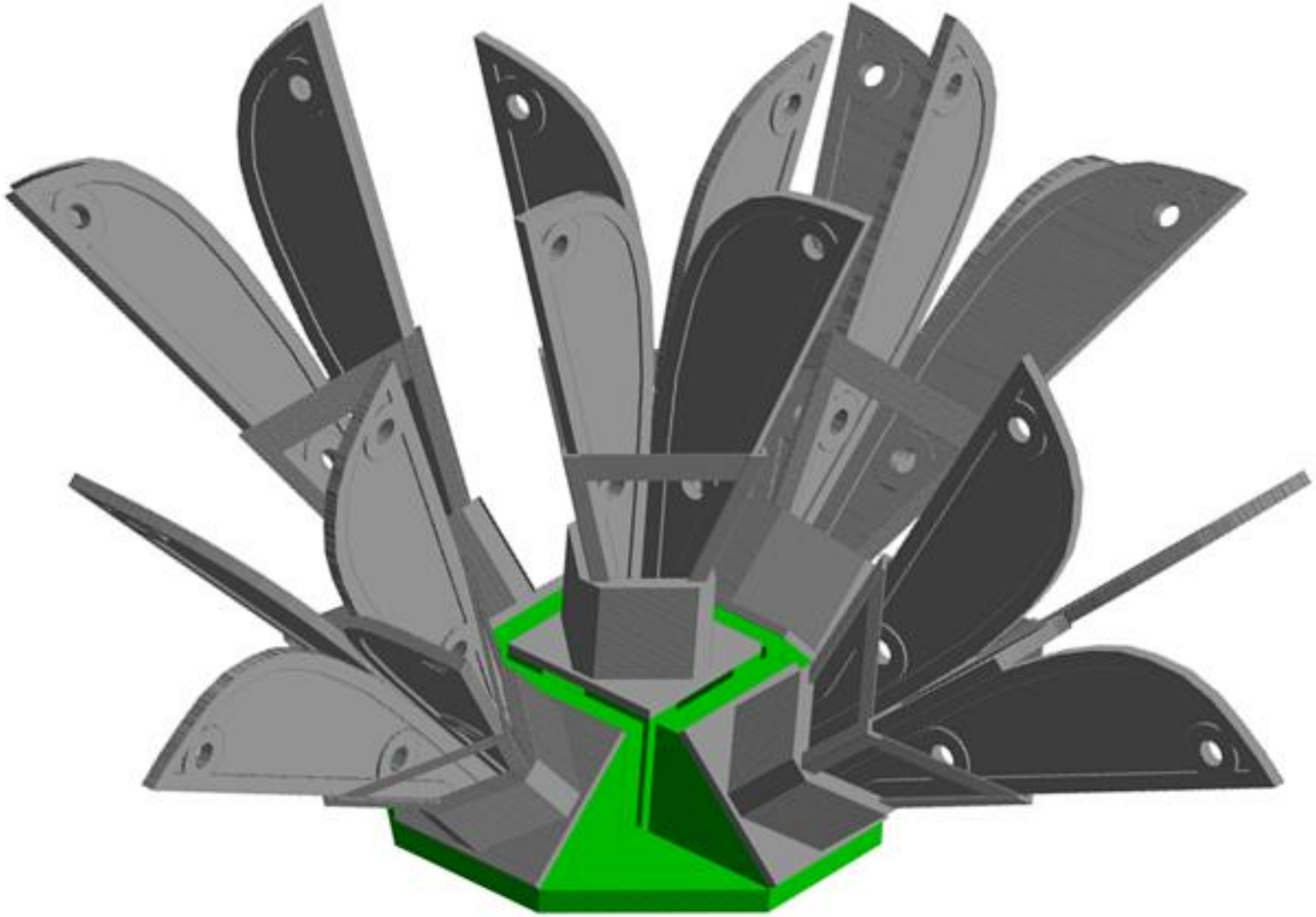



0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
V/m

Simulation example:
Visible Human Phantom (VHP)

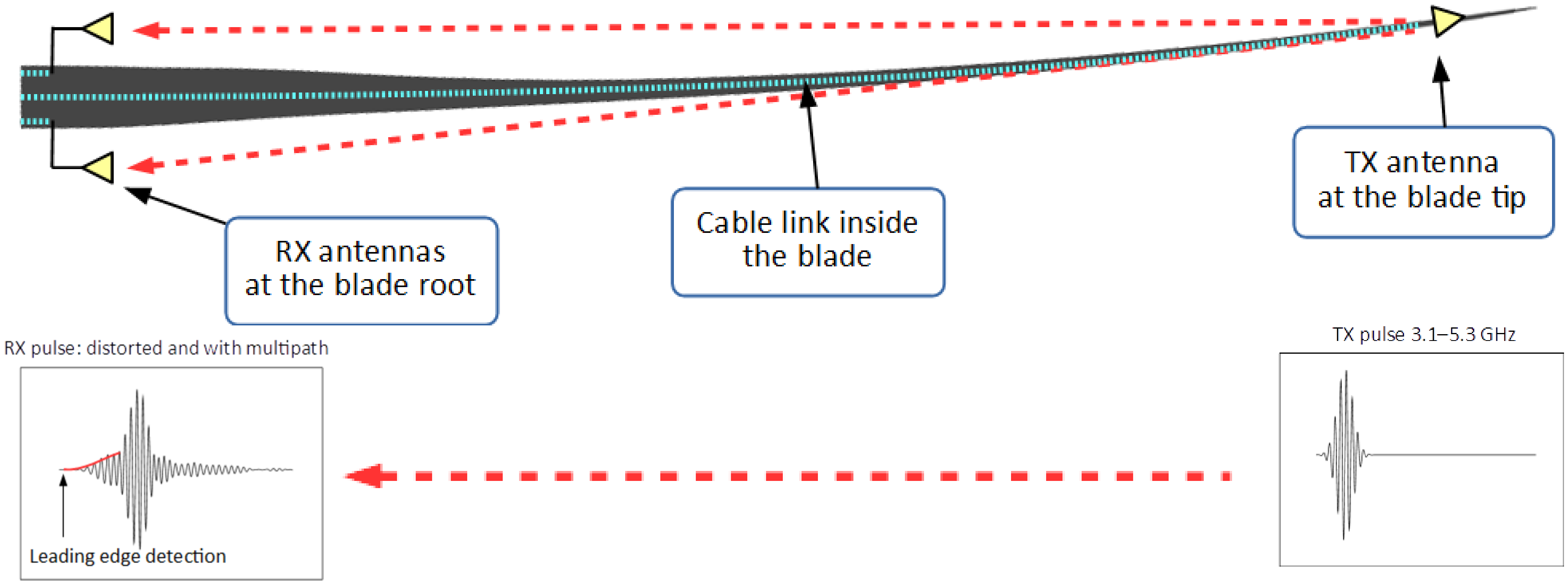


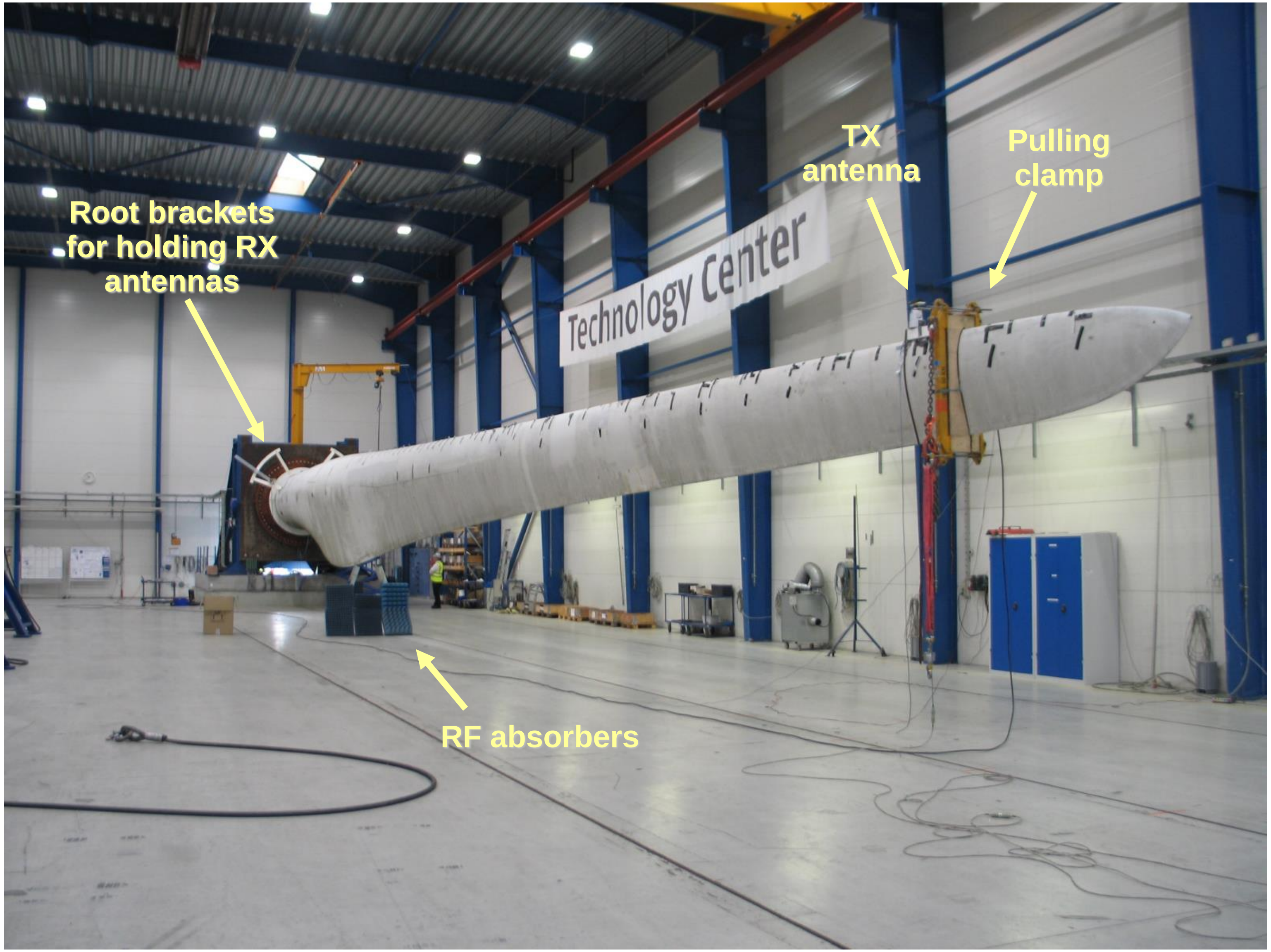
Simulation example: Channel sounding antenna array



Deflection Sensing System with UWB Radio Links: **iRotor**

- Bending of the blade changes the distance between the TX and RX antennas
- The distance is determined by detecting the pulse time of arrival
- The received pulse will be affected by multipath interference due to the blade





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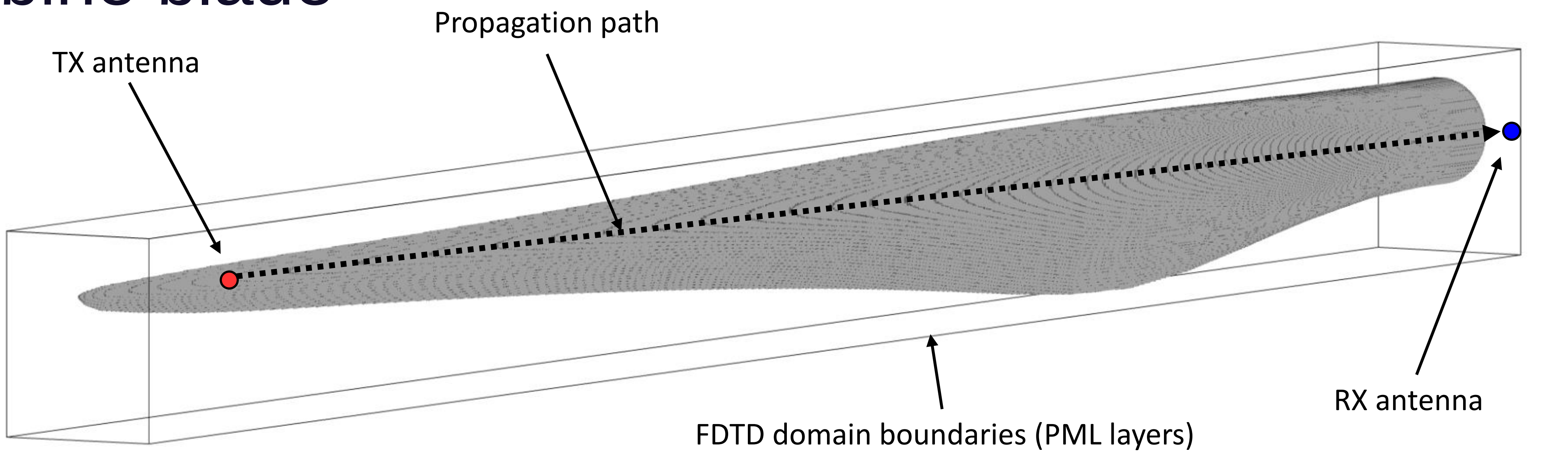
Simulation example: Radiowave propagation along a wind turbine blade



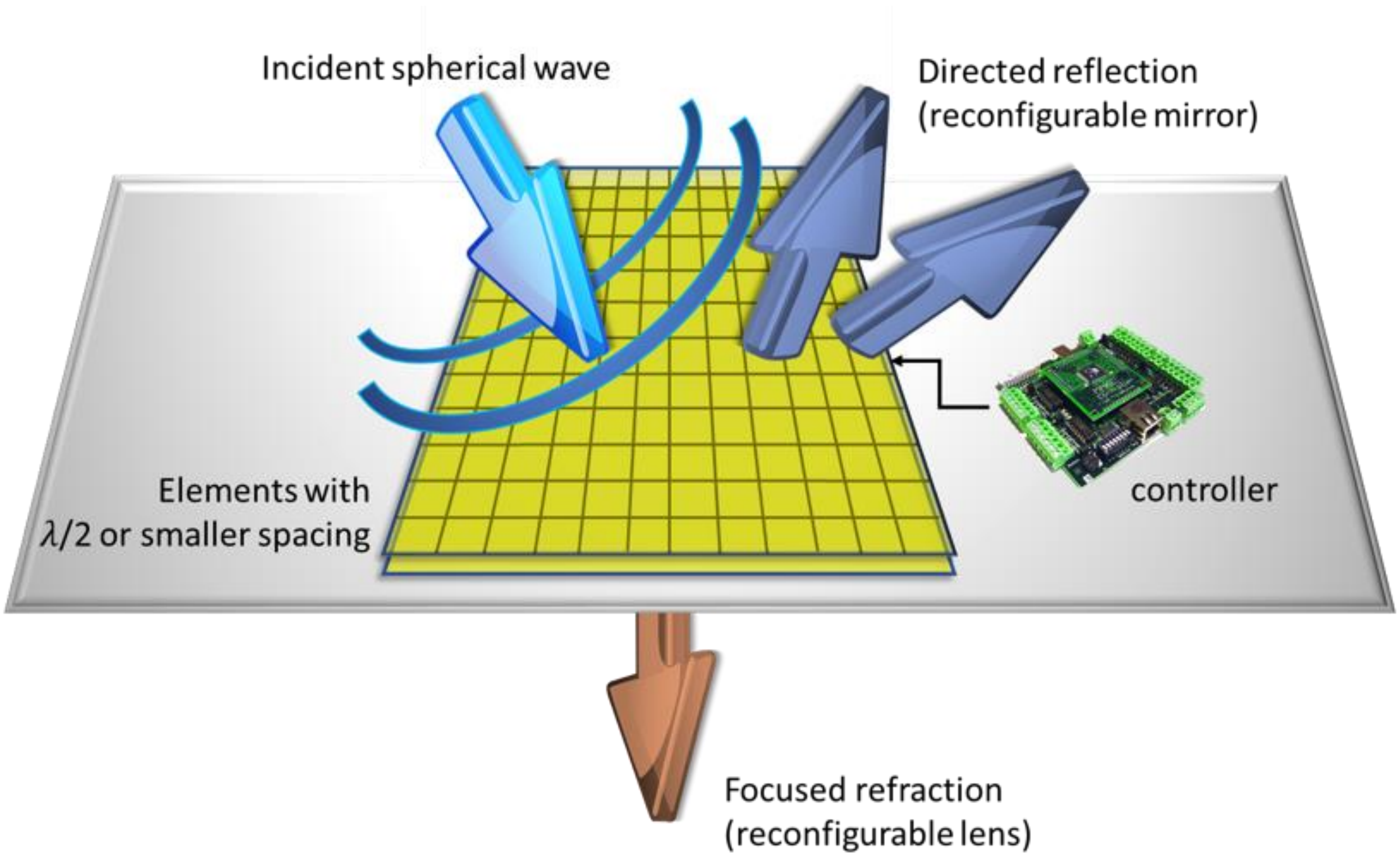
- Blade length: 58.7 meters
- Discretized into 5mm Yee cubes
- Computational domain of 864 x 1045 x 11924 cells = >10 billion mesh cells

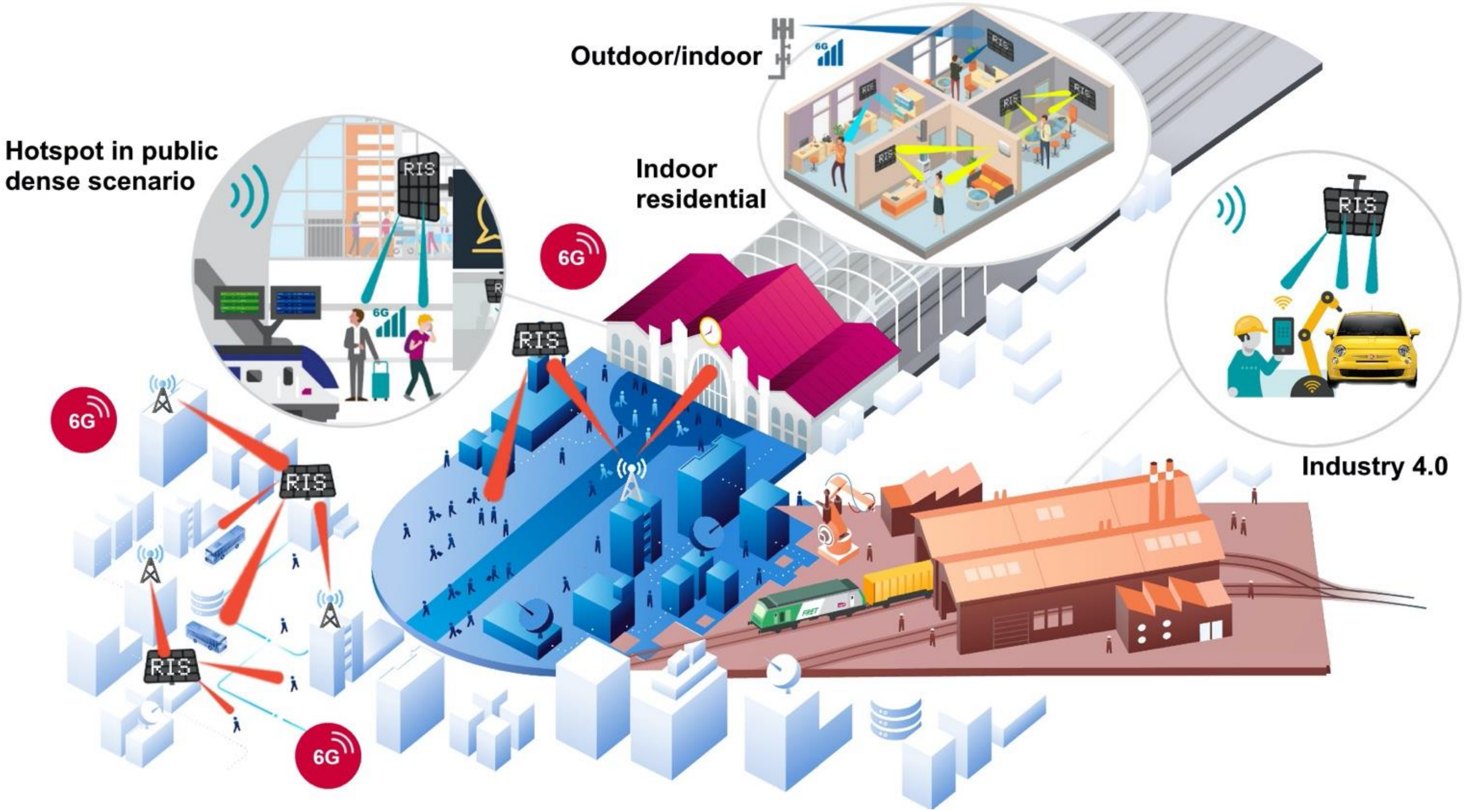
RISE-6G PROJECT

- **R**econfigurable **I**ntelligent **S**ustainable **E**nvironments for **6G** Wireless Networks
- EU H2020 project
- Research and Innovation action
- Smart Connectivity beyond 5G - ICT-52

RISE-6G will design, prototype, and trial radical technological advances based on Reconfigurable Intelligent Surfaces (RISs) to forge a new generation of dynamically programmable wireless propagation environments. This will support dynamic adaptation to future stringent and highly varying B5G/6G service requirements in terms of Electromagnetic Field (EMF) emissions, localization accuracy, Energy Efficiency (EE), secrecy guarantees, as well as legislation and regulation changes, while incurring minimal connect-compute network redesign and reconfiguration costs.

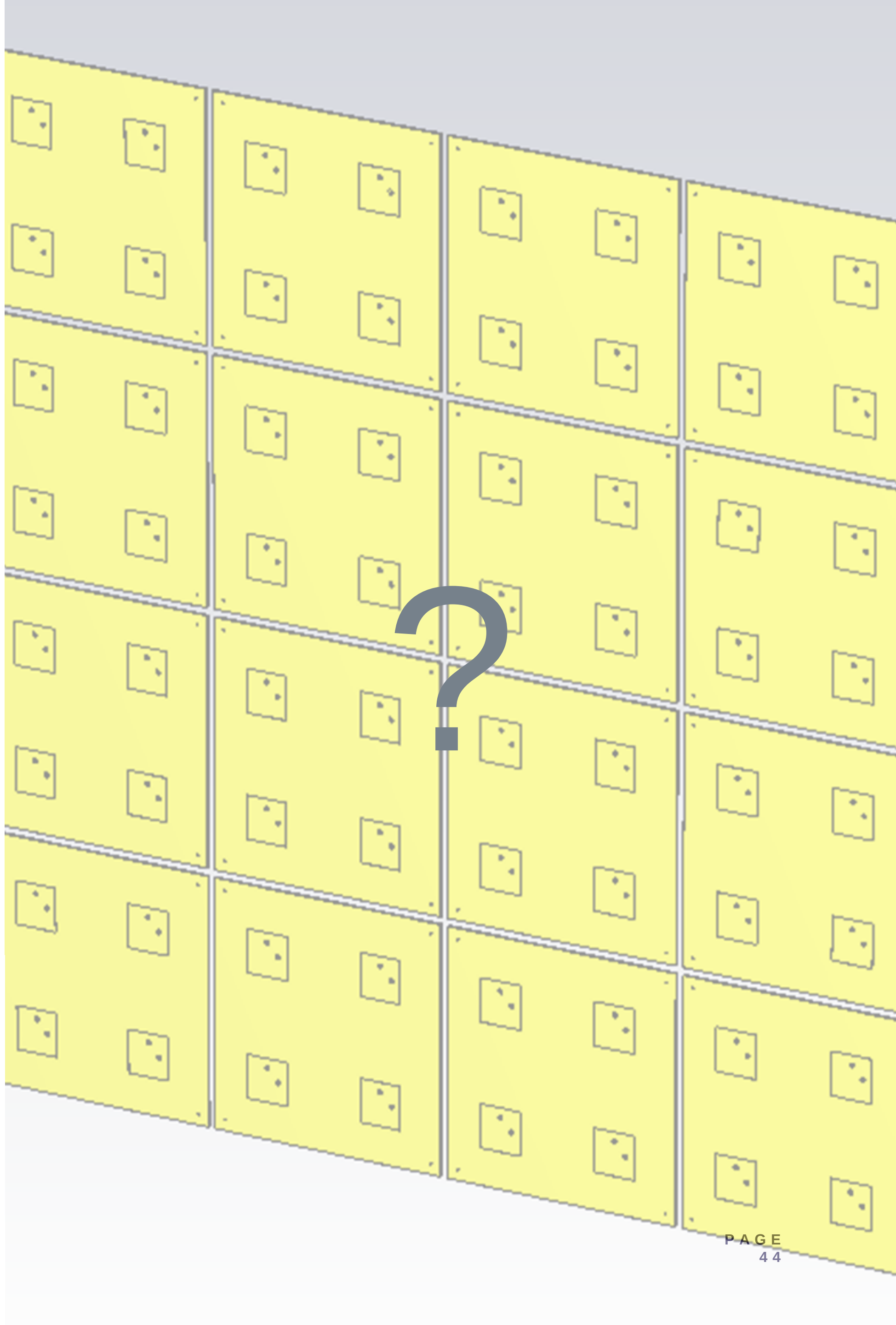
Reconfigurable Intelligent Surface (RIS)




Outdoor/indoor
Hotspot in public dense scenario
Indoor residential
Industry 4.0
RIS
RIS
RIS
RIS
RIS
6G
6G
6G
6G

Future RIS design

- What is the optimum shape?
- What are the physical bounds?
- Antennas are characterized by radiation patterns -> function of 2 variables
- Scatterers (such as RIS) are characterized by radar cross section (RCS) -> function of 4 variables!
- Large scale search and optimization
- …with help of LUMI



THANK YOU!

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