How much wireless power does a person absorb?

Robin Wydaeghe Promotors: Wout Joseph and Emmeric Tanghe

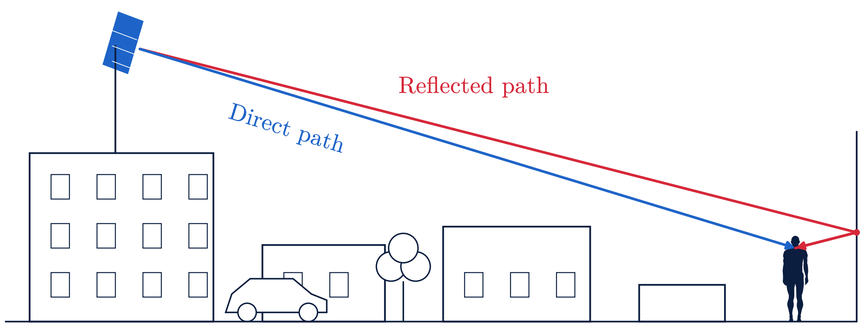
WAVES, Department of Information Technology, Ghent University – imec, Belgium

Whole-thesis overview

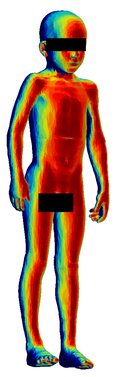
2 Full-wave reference	3 Indoor hybrid method	4 Outdoor hybrid method	5 Closed-form dosimetry	6 Measurements and cities

Radio waves carry information to a phone. Some of that energy is absorbed in the body. The task is to calculate this absorption from the antennas, the surroundings and the person. The methods include detailed body simulations, hybrid models for rooms and streets, and fast absorption formulas.

Wireless environment: ~100 m

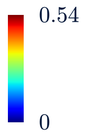


Human body: ~1 m



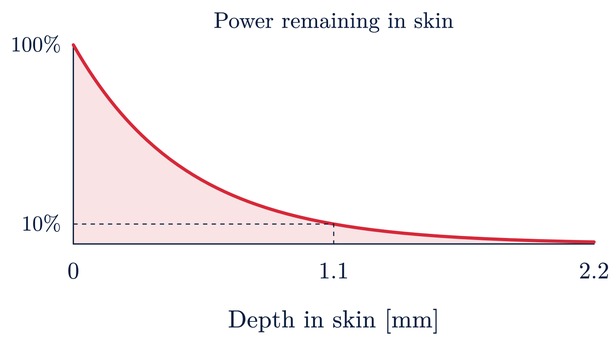
Example: 28 GHz
1 W/m² incident

Absorbed power density [W/m²]



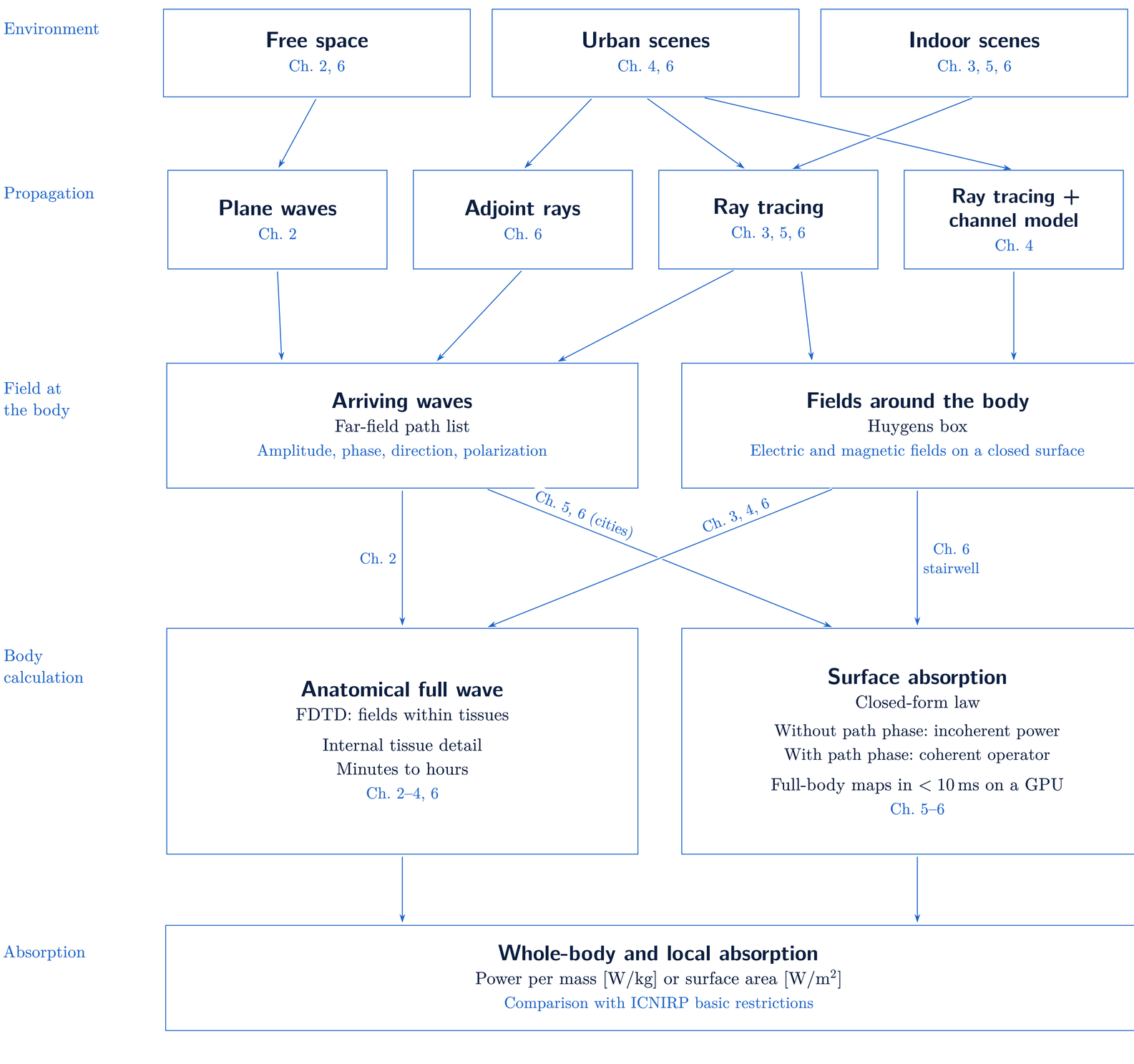
Absorbing tissue: ~ 1 mm

26 GHz: 90% absorbed within 1.1 mm



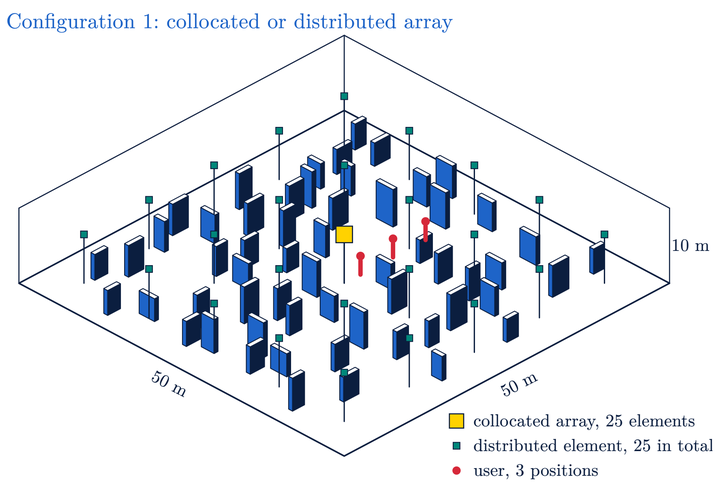
From the environment to absorbed power

The diagram shows how the propagation and body models fit together.

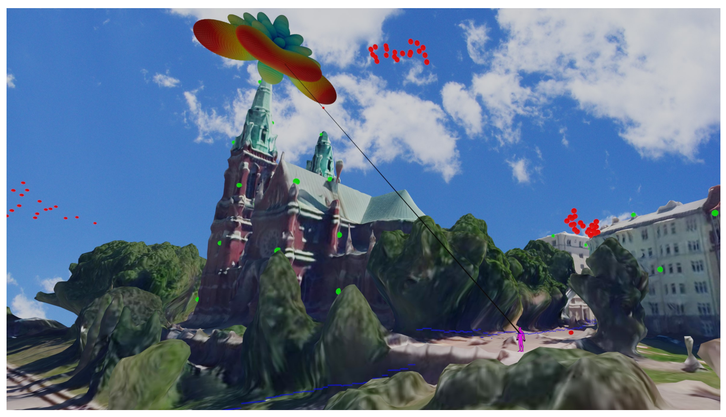


Indoor and outdoor scenes

Factory hall, Ch. 3



Helsinki at 28 GHz, Ch. 4



Antennas are either grouped on the church tower or distributed across building façades. Green: access points. Red: channel-model scatterers. The methods also have a city-scale application on ten routes in Chapter 6.

Exposure-aware beam design

Coherent operator, Ch. 5

Whole-body absorbed power: median 5.29-fold reduction at half the maximum signal power (simulation)

Body size and frequency

We ran 550 simulations with four bodies at 15 frequencies. Below 6 GHz, the child models absorb 1.5–1.9 times as much power per kilogram as the adults at the same incident power density, averaged over six directions.

Deployment and phase

At equal total radiated power, distributed arrays have 2–3 times lower exposure than collocated arrays in the factory. The outdoor cell-free case also has less variation along the walk.

Limits and open questions

We measured in an anechoic chamber and a stairwell. Absorption in idealized reference-level fields can be above a limit. The studied realistic scenarios are well below the limits. Outdoor validation, moving bodies and time averages are future work.

Sources R. Wydaeghe, *Hybrid computational methods for 6G exposure assessment*, PhD thesis, Ghent University, 2026, Chapters 2–7. The route map follows the Chapter 7 synthesis.
Selected papers: *Phys. Med. Biol.* (2026), doi: 10.1088/1361-6560/ae97ac. *IEEE Access* (2022), doi: 10.1109/ACCESS.2022.3227107. *npj Wireless Technology* (2026), doi: 10.1038/s44459-026-00031-4. Ch. 5 and the journal studies in Ch. 6 are submitted manuscripts. Exposure limits: ICNIRP 2020.

Acknowledgement
Supported through ERC ATTO (695495), Methusalem SHAPE and EU GOLIAT (101057262). Anatomical models: IT'IS Virtual Population. Health effects were not tested.

Publications

imec waves wireless, acoustics, environment & expert systems

GHENT UNIVERSITY

Full-wave dosimetry of adults and children from 450 MHz to 26 GHz

Robin Wydaeghe[1], Bram Stroobandt[1], Silvia Gallucci[2], Marta Parazzini[2], Gabriella Tognola[2], Joe Wiart[3], Günter Vermeeren[1], Mònica Guxens[4], Emmeric Tanghe[1], and Wout Joseph[1]

[1] WAVES, Department of Information Technology, Ghent University – imec, Belgium [2] CNR-IEIIT, Milan, Italy [3] Télécom Paris, Institut Polytechnique de Paris, France [4] ISGlobal, Barcelona, Spain

2 Full-wave reference | **3** Indoor hybrid method | **4** Outdoor hybrid method | **5** Closed-form dosimetry | **6** Measurements and cities

Children absorb 1.5 to 1.9 times as much power per kilogram as adults below 6 GHz. At the reference level, whole-body SAR in the six-year-old is 93% of the limit averaged over 12 plane waves, and 145% for the worst of them.

1 Question

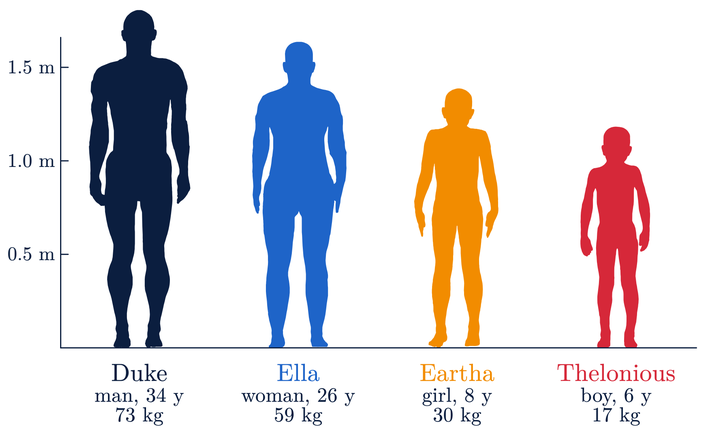
Exposure guidelines limit the power absorbed inside the body. These basic restrictions cannot be measured in a person, so the guidelines also specify reference levels for the incident field outside the body. Below the reference level, absorbed power should be below the basic restriction.

We check this relation for adults and children at 15 frequencies between 450 MHz and 26 GHz, for plane waves from six directions and for a beam focused on the user.

Basic restriction [2]	**Limit**	**Applies**
Whole-body SAR	0.08 W/kg	all frequencies
Peak SAR over 10 g	2 W/kg	head, torso, to 6 GHz
Absorbed power density	20 W/m^2	4 cm^2, above 6 GHz
Reference level [2]	10 W/m^2	above 2 GHz

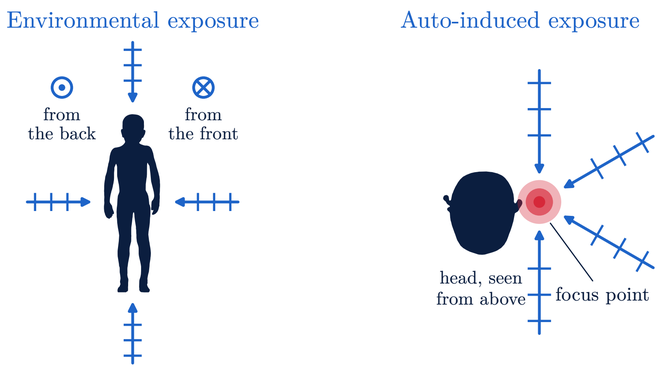
ICNIRP 2020 values for the general public. SAR: specific absorption rate. Below 2 GHz the reference level decreases to 2.25 W/m^2 at 450 MHz.

2 Method



Four body models of the Virtual Population [3], each with more than 300 tissues and organs.

We solve Maxwell's equations on a grid with the finite-difference time-domain (FDTD) method. The cell size decreases from 2.5 mm at 450 MHz to 0.3 mm at 26 GHz, and the cost increases with the fourth power of the frequency.



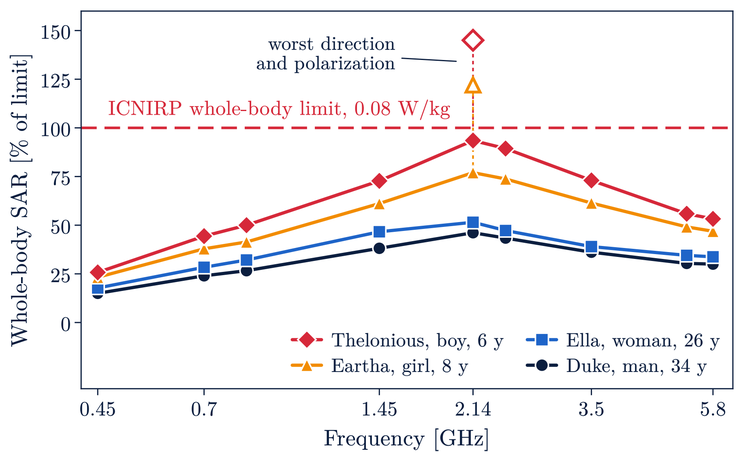
Exposure types. Left: 12 plane waves, six directions with two polarizations each. Right: four plane waves that add in phase at a focus point near the skin.

For the focused beam, wave i of $N = 4$ has the weight

$$w_i = \frac{1}{\sqrt{N}} e^{-j \arg E_{z,i}(\mathbf{r}_0)}, \qquad \mathbf{E}(\mathbf{r}) = \sum_{i=1}^{N} w_i \, \mathbf{E}_i(\mathbf{r}),$$

with $E_{z,i}$ the vertical electric field of wave i at the focus point $\mathbf{r}_0$, and $\mathbf{E}_i$ the simulated field of wave i in the whole body.

3 Absorption per kilogram



Whole-body SAR for an incident field at the ICNIRP reference level [2], averaged over 12 plane waves. Open markers: worst single plane wave at 2.14 GHz.

The whole-body specific absorption rate is

$$\mathrm{SAR}_{\mathrm{wb}} = \frac{\mathrm{ACS} \cdot S}{m},$$

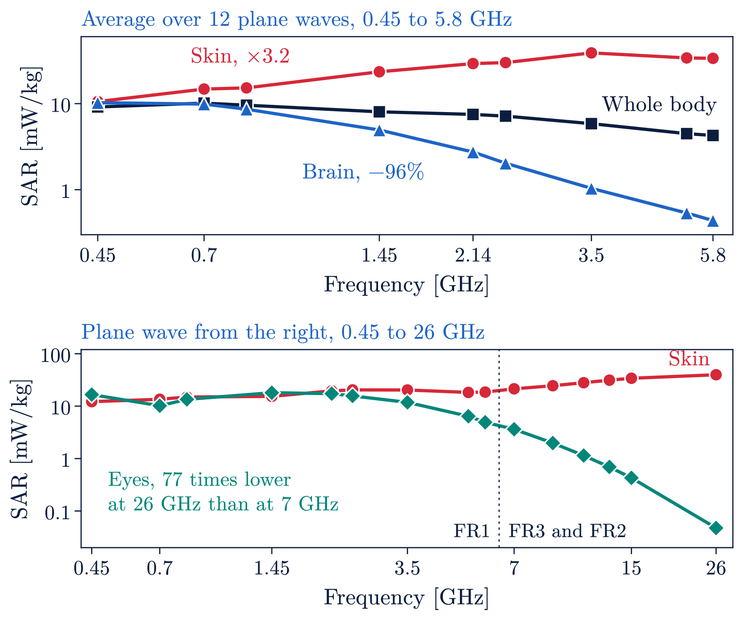
with ACS the absorption cross section [m^2], S the incident power density [W/m^2], and m the body mass [kg].

A child has a smaller cross section, but its mass is smaller still. The children's $\mathrm{SAR}_{\mathrm{wb}}$ is therefore 1.5 to 1.9 times the adult value below 6 GHz. The adult average is below 52% of the limit.

550
simulations, 15 frequencies, 4 body models

1.84×10^9
grid cells for one simulation at 26 GHz

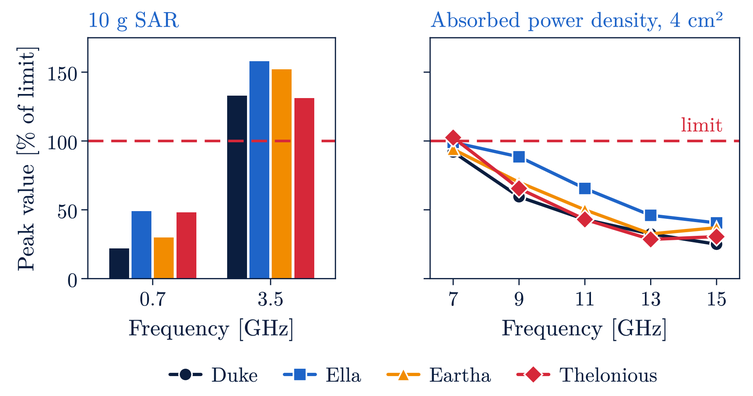
4 Absorption per tissue



SAR per tissue in the six-year-old model for an incident power density of 1 W/m^2.

The 90% power absorption depth decreases from 60 mm in muscle at 450 MHz to 1.1 mm in skin at 26 GHz. Therefore, skin SAR increases and brain SAR decreases with frequency. At 26 GHz the closed eyelid absorbs the field before it reaches the eye.

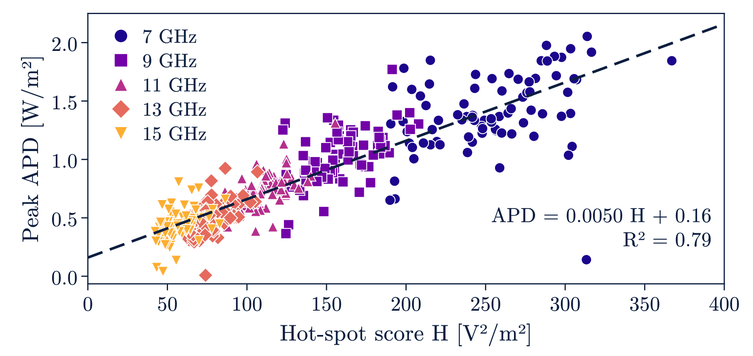
5 Exposure to a focused beam



Highest evaluated focus point per body model, for four waves whose power densities sum to the reference level. Left: peak SAR over 10 g. Right: APD over 4 cm^2. At 0.7 GHz, Duke and Eartha peak in the leg (4 W/kg limit).

The reference levels are set for a uniform plane wave. A focused beam with the same incident power density concentrates the field in a hot-spot. At 3.5 GHz the peak SAR over 10 g is 131 to 158% of the limit for all four models. At 7 GHz the APD is 92 to 103%, near the limit within the ±12% modelling uncertainty. At 15 GHz the hot-spot is smaller than the averaging area, and the APD is 25 to 40% of the limit.

6 Search for the worst focus point



Score against APD for 400 focus points at an incident power density of 1 W/m^2.

A full evaluation at every focus point costs too much. Therefore, we rank 10 000 candidate points per case with a score H, the mean of $|\mathbf{E}|^2$ over the skin in a cube of 50 mm around the point. Only the best 20 are fully evaluated, at 1/500 of the cost.

7 Conclusions

- At the reference level, a child can exceed the whole-body limit: 145% for the worst plane wave at 2.14 GHz.
- A focused beam at the reference level exceeds the 10 g SAR limit at 3.5 GHz. At 7 GHz the APD is at the limit within the ±12% modelling uncertainty.
- Measured exposure in daily life is three to four orders of magnitude below the reference level.
- Above 6 GHz the skin absorbs the field. Chapter 5 uses this property to replace the simulation with a formula.
- All results and the simulation framework are openly available [1].

References

[1] R. Wydaeghe *et al.*, "Environmental and auto-induced RF-EMF adult and children far-field exposure simulations between 450 MHz and 26 GHz," *Phys. Med. Biol.*, vol. 71, no. 17, art. no. 175006, 2026, doi: 10.1088/1361-6560/ae97ac. [2] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, 2020. [3] M.-C. Gosselin *et al.*, "Development of a new generation of high-resolution anatomical models for medical device evaluation: the Virtual Population 3.0," *Phys. Med. Biol.*, vol. 59, no. 18, 2014. Data: doi: 10.7910/DVN/EEEE0X.

Acknowledgement

The GOLIAT project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101057262.

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Exposure of a user in a factory hall with massive MIMO at 3.5 and 28 GHz

Robin Wydaeghe, Sergei Shikhantsov, Emmeric Tanghe, Günter Vermeeren, Luc Martens, Piet Demeester, and Wout Joseph
WAVES and IDLab, Department of Information Technology, Ghent University – imec, Belgium

At equal radiated power, user exposure is two to three times lower with a distributed antenna array than with a collocated array. In this comparison at 320 W, the 95th percentile of exposure is at most 4% of the ICNIRP limits.

1 Question

A massive multiple-input multiple-output (MIMO) base station uses many antenna elements to focus its power on the user. The focus is a hot-spot at the device, and its shape and strength depend on the walls and machines of the hall.

A full-wave simulation of the hall is not possible. At 28 GHz the wavelength is 10.7 mm and the hall is 50 m across. A simulation of the head alone does not contain the hall. Therefore, we use a hybrid method. We ask how the layout of the array changes the exposure.

Exposure quantity	Evaluated	Limit [2]
Incident power density	in free space	10 W/m^2
Peak SAR in 10 g	in the head, 3.5 GHz	2 W/kg
Absorbed power density	on 4 cm^2 of skin, 28 GHz	20 W/m^2

The first quantity has a reference level and the others have basic restrictions. SAR: specific absorption rate.

We report every quantity γ as a percentage of its limit, for a radiated power of 320 W:

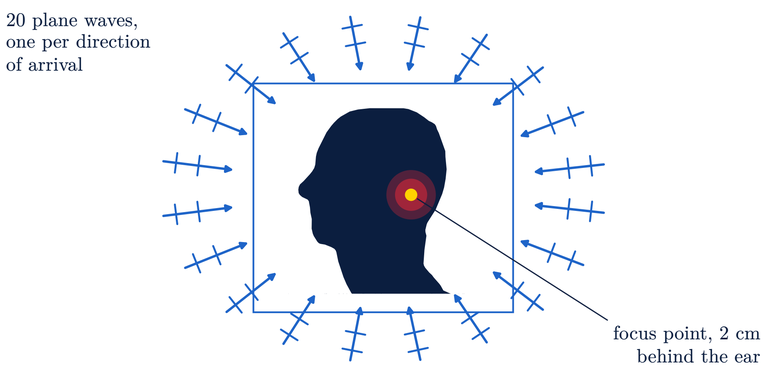
$$\eta = \frac{\gamma}{\gamma_{\text{limit}}}, \qquad \alpha = \frac{\eta_{\text{b}}}{\eta_{\text{r}}},$$

with η_{r} for the reference quantity and η_{b} for the basic quantity. If α is below 1, the head quantities are below the basic restriction when the field is at the reference level.

2 Hybrid method

1. Ray tracing hall, array, user rays per element → **2. FDTD** one plane wave per direction → **3. Combination** weighted sum of the head fields

Ray tracing computes the paths of the waves from every antenna element through the hall, with up to six reflections and two diffractions. At the user, we group the rays into 20 directions.



Head simulation. The finite-difference time-domain (FDTD) method solves Maxwell's equations in the anatomical head model MIDA [3]. Blue frame: simulated volume, with 1.5 million cells of 1.75 mm at 3.5 GHz and 22 million cells of 0.72 mm at 28 GHz. A simulation per direction is enough for all arrays and channels.

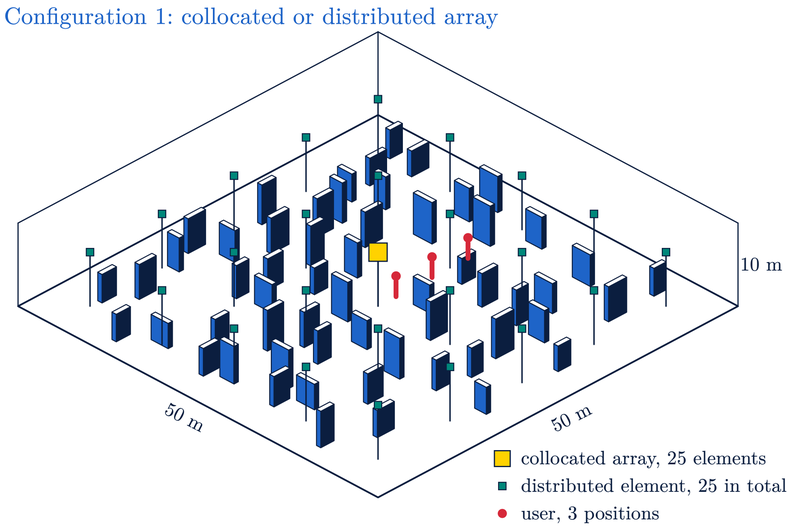
The base station sets the phases of its M elements so that their waves add in phase at the user's device. With the channel h_m of element m, the weights and the total field are

$$w_m = \frac{h_m^*}{\|\mathbf{h}\|}, \qquad \mathbf{E}_{\text{tot}}(\mathbf{r}) = \sum_{i=1}^{20} a_i \, \hat{\mathbf{E}}_i(\mathbf{r}),$$

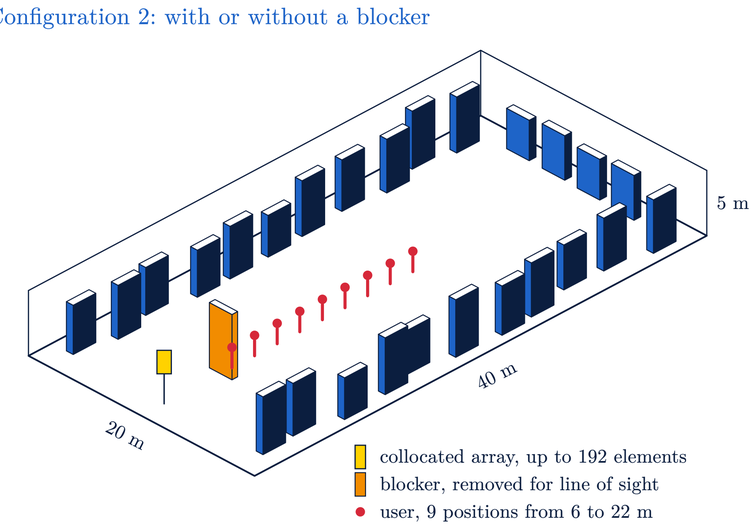
with $\hat{\mathbf{E}}_i$ the field in the head for a unit plane wave from direction i, and a_i the complex amplitude of the weighted rays from that direction.

3 Factory halls

Configuration 1: collocated or distributed array

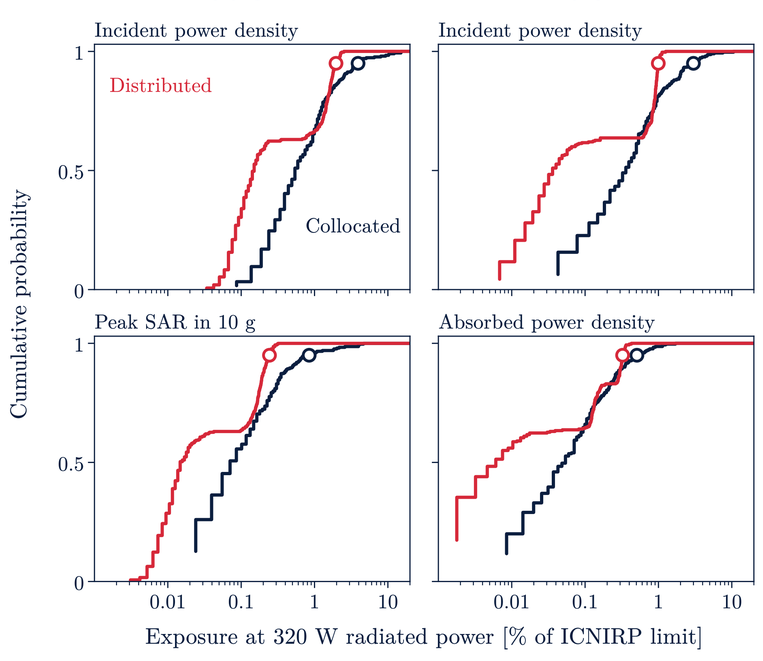


Configuration 2: with or without a blocker



Concrete halls with metal objects placed at random for every channel realization. Left: 100 realizations with three users. Right: five realizations with nine users.

4 Collocated or distributed



Distribution of the exposure over all users and channel realizations in configuration 1. Circles: 95th percentile. Top: reference quantity in free space. Bottom: basic quantity in the head.

Exposure is two to three times lower with the distributed array. The two groups may be due to machinery. With surrounding machines, the nearest elements contribute most. Otherwise, distant elements contribute too.

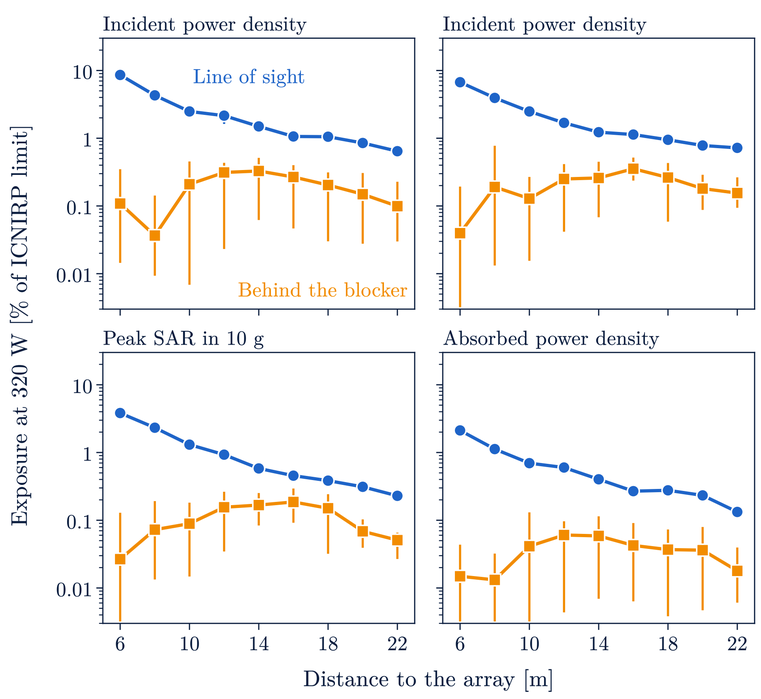
The head quantities are 5 to 10 dB further below their limits than the incident power density. Thus, $\alpha < 1$ in these simulations.

Most groups are absent after device-power normalization. The main cause is propagation, except possibly near-skin APD hot-spots with the distributed array at 28 GHz.

4% of the reference level, 95th percentile at 320 W

0.85% of the basic restrictions, 95th percentile at 320 W

5 Line of sight or blocked



Exposure against distance in configuration 2. Markers: mean. Bars: range over five realizations.

In line of sight, the exposure decreases with distance as a power law. Behind the blocker it is about 100 times lower close to the array and 2 to 10 times lower from 12 m on. The blocker is 5 m from the array.

6 Conclusions

- The hybrid calculation uses ray tracing for a 50 m hall and FDTD for the head at 28 GHz.
- Exposure is two to three times lower with a distributed array at equal radiated power.
- With the incident field at the reference level, the head quantities are 5 to 10 dB below their limits.
- Close to the array, a blocker lowers exposure by up to about 100 times.
- Chapter 4 applies the method outdoors, in a city street.

References

[1] R. Wydaeghe *et al.*, "Realistic human exposure at 3.5 GHz and 28 GHz for distributed and collocated MaMIMO in indoor environments using hybrid ray-tracing and FDTD," *IEEE Access*, vol. 10, pp. 130996–131004, 2022, doi: 10.1109/ACCESS.2022.3227107. [2] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, 2020. [3] M. I. Iacono *et al.*, "MIDA: a multimodal imaging-based detailed anatomical model of the human head and neck," *PLoS ONE*, vol. 10, no. 4, 2015.

Acknowledgement

This work was supported by the European Research Council (ERC) through ATTO: A New Concept for Ultrahigh Capacity Wireless Networks, under Grant 695495, and by Methusalem through SHAPE: Next Generation Wireless Networks.

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Exposure of a pedestrian in a 6G cell-free network at 28 GHz, street by street

Robin Wydaeghe, Sergei Shikhantsov, Günter Vermeeren, Luc Martens, Emmeric Tanghe, and Wout Joseph
WAVES, Department of Information Technology, Ghent University – imec, Belgium

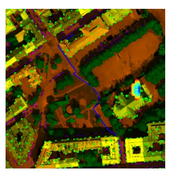
At equal total network power, cell-free exposure varies about 20 dB less along the walk than with a collocated array. Snapshot maxima are below 1% of the local power-density thresholds in both studied cities.

1 Question

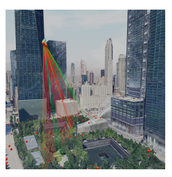
A cell-free network replaces a large antenna array with hundreds of small access points on the facades. Their phases are coordinated so that the waves add in phase at the device. Does this change the exposure of the pedestrian who holds it?

The answer depends on the street, where buildings, trees and cars block and reflect waves of 10.7 mm. The body absorbs the power in the first millimeter of skin. Both the street and the body are part of the model.

2 Method in New York



1 Configuration
Two addresses are the endpoints of the walk. The area has a photogrammetric 3D mesh. A neural network assigns every face to one of six classes, such as building, vegetation or terrain. Each class has a material.



2 Propagation
The large-scale channel parameters are from ray tracing at a coarse set of points along the walk. A stochastic channel model [3] computes the channel at every position, continuous in time.

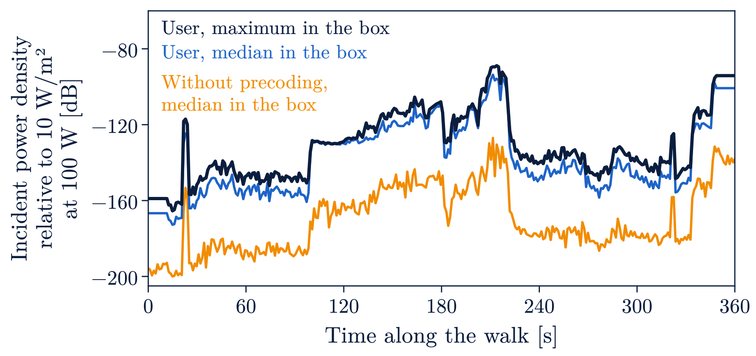


3 Hybridization
The last scatterers of the channel model radiate to the user. Their fields are summed, with the precoding weights, on a Huygens box around the ear.



4 Exposure
The box is the source of a finite-difference time-domain (FDTD) simulation with an anatomical head model at 0.5 mm resolution. The output is the absorbed power density over 4 cm^2 of skin.

3 New York: a walk of six minutes



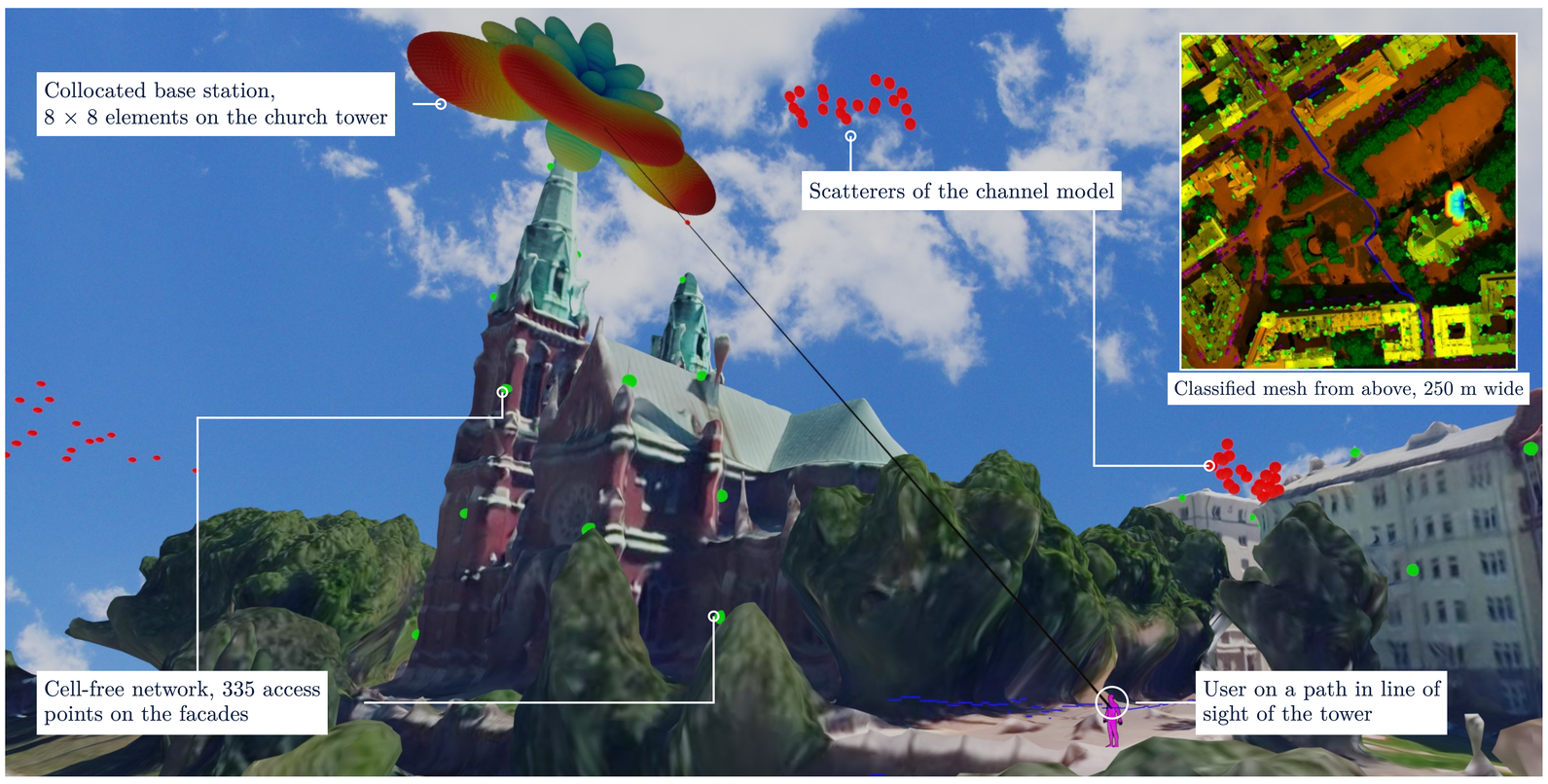
Walk at the World Trade Center, device at the right ear, 100 W total. The normalization of 10 W/m^2 is below the local reference level of 30.5 W/m^2. Box: 5.1 cm × 4.1 cm × 7.1 cm around the ear.

User exposure with precoding is 32 dB higher than with unprecoded transmission. The signal at a pedestrian 5 m away is 10 dB lower. The box maximum is 7 dB above its median.

9905
Helsinki positions, 160 s each on GPU hardware

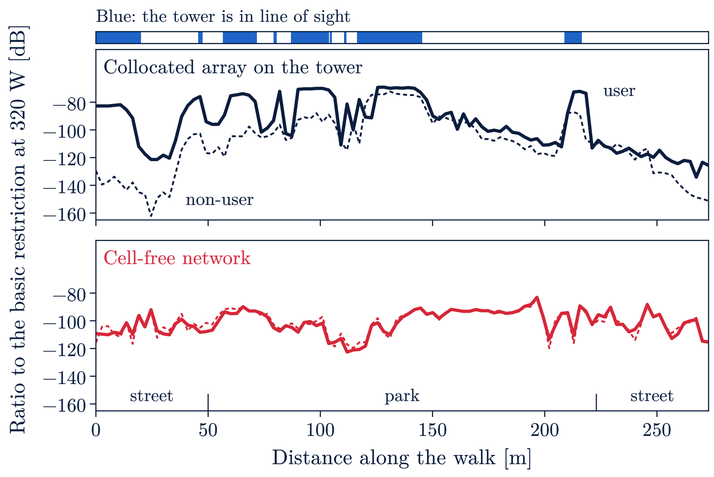
< 1%
snapshot maxima relative to local thresholds, both cities

4 Helsinki: collocated array and cell-free network



St. John's Church as a photogrammetry mesh. The beam of the collocated array (colored pattern) is directed at the user. Green: access points of the cell-free network. Red: scatterers for this position. Inset: the 273 m walk in blue. Here the mesh is used for the channel model's line-of-sight classification. This case has no ray tracing.

5 Exposure along the walk

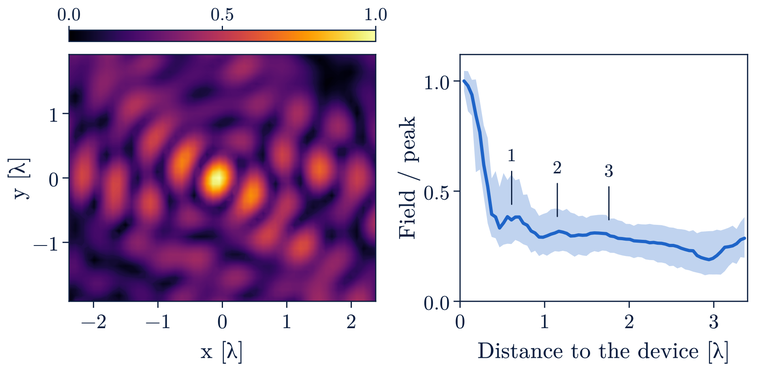


Absorbed power density over 4 cm^2, relative to the limit of 20 W/m^2, for 320 W in total. Solid: user. Dashed: non-user, without precoding.

With the array on the tower, the exposure is high where the tower is in line of sight. The user's exposure is higher than the non-user's, because the beam is directed at the device.

In the cell-free network, an access point is in line of sight most of the time. The user and non-user curves nearly coincide, and exposure varies about 20 dB less along the walk at equal total network power.

6 Hot-spot at the device



Electric field around the device, averaged over 316 positions of the New York walk, relative to the peak. Right: field against distance, with three sidelobes.

At a given instant, the hot-spot can have any shape. Averaged over the walk, the field has a peak at the device, 0.44 λ wide. Far from the device, the field is 25% of the peak, so the time-averaged field at the hot-spot is 12 dB higher.

The quantity averaged under the guidelines [2] is power:

$$S_{\text{field}} = |\langle \mathbf{E} \rangle \times \langle \mathbf{H} \rangle|, \qquad S_{\text{power}} = \langle |\mathbf{E} \times \mathbf{H}| \rangle,$$

with $\langle \cdot \rangle$ the average over time. In S_{power}, fields of opposite sign no longer cancel, and the peak is 0.92 λ wide.

7 Conclusions

- The power absorbed in a pedestrian's skin is calculated from the network's precoding weights in a 3D model of an existing street.
- Exposure is more uniform with a cell-free network than with a collocated array, for users and non-users.
- Each hybrid-method position takes 160 s on GPU hardware. The FDTD cost is proportional to the fourth power of frequency. The closed-form law of Chapter 5 is an alternative to FDTD.

References
[1] R. Wydaeghe *et al.*, "Hybrid ray-tracing-QuaDRiGa/FDTD method for realistic 28 GHz exposure with 6G CF-MaMIMO in 3D outdoor environments," *npj Wireless Technology*, vol. 2, art. 13, 2026, doi: 10.1038/s44459-026-00031-4. [2] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, 2020. [3] S. Jaeckel *et al.*, "QuaDRiGa: a 3-D multi-cell channel model with time evolution for enabling virtual field trials," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, 2014.

Acknowledgement
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Read the paper

A closed-form law for the power absorbed by the human body above 6 GHz

Robin Wydaeghe, Luc Martens, Günter Vermeeren, Emmeric Tanghe, and Wout Joseph
WAVES, Department of Information Technology, Ghent University – imec, Belgium

The absorbed power density on the whole body surface is calculated in less than 10 ms with a closed-form law. Averaged over directions, agreement with FDTD is within 3%. With wave phase included, absorbed power with the resulting beamformer is five times lower at half the signal power.

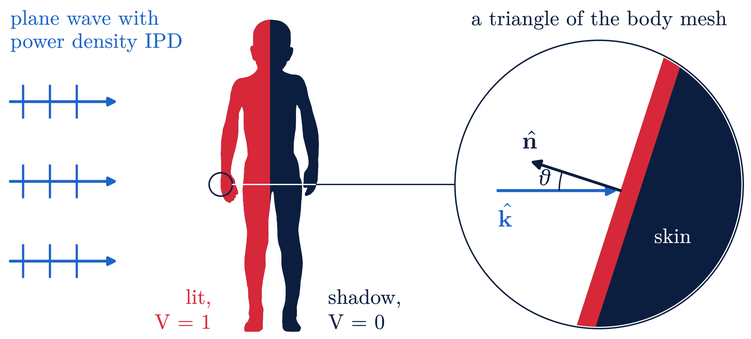
1 Question

Above 6 GHz, the skin absorbs a wave within a few millimeters. Therefore, the basic restriction in the ICNIRP guidelines [3] is on absorbed power density (APD) at the skin, in $\mathrm{W/m^2}$.

A finite-difference time-domain (FDTD) simulation has to resolve this millimeter over the whole body. The grid needs 10^8 cells at 6 GHz and 10^{12} cells near 100 GHz. For volunteer studies, fitted absorption coefficients are between 0.4 and 0.7. No body simulation is needed.

Can body shape and skin properties predict these coefficients and the APD map?

2 Absorption at a point on the skin

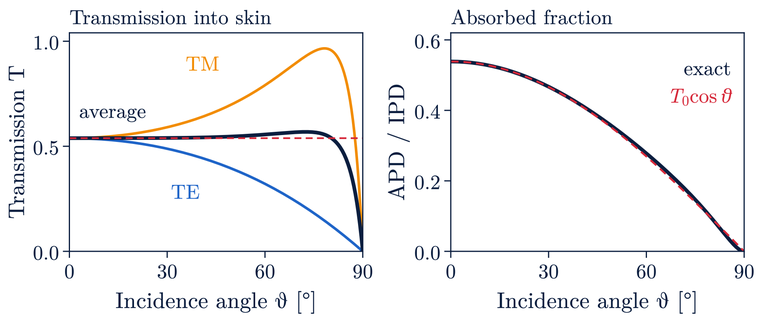


A plane wave on the body mesh. Every triangle has a normal $\hat{\mathbf{n}}$. The wave arrives along $\hat{\mathbf{k}}$ at the angle θ.

At these frequencies the body is opaque and its surface is flat on the scale of the wavelength. Each triangle then absorbs like a flat sheet of skin:

$$\mathrm{APD} = \mathrm{IPD}\; T_0 \left[\hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}})\right]_+ V, \qquad T_0 = \frac{4\,\mathrm{Re}(\tilde{n})}{|1+\tilde{n}|^2},$$

with IPD the incident power density, T_0 the transmission of skin at normal incidence, $\tilde{n}$ the complex refractive index of skin, $[\,\cdot\,]_+$ the positive part, which equals $\cos\theta$ on the lit side, and V the visibility, 1 if the triangle is lit and 0 otherwise.



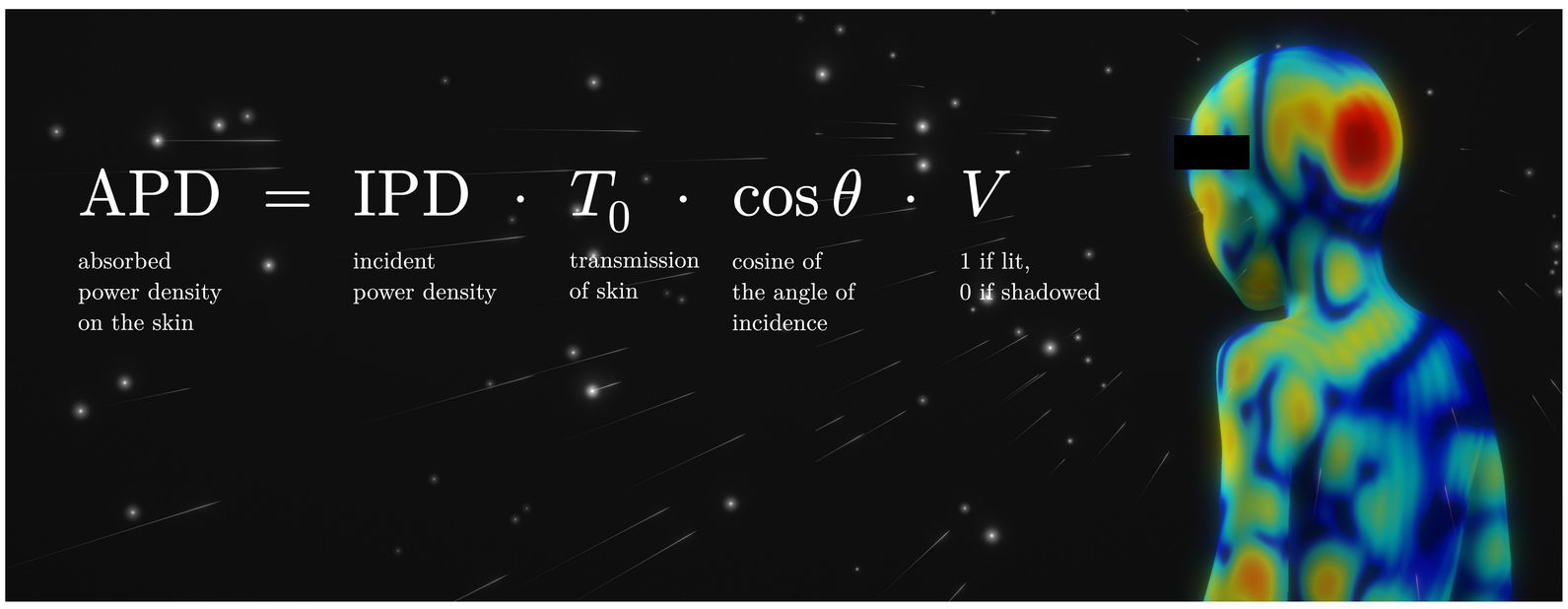
Skin at 28 GHz, $\tilde{n} = 4.49 - 1.79\mathrm{i}$ and $T_0 = 0.54$. Left: both polarizations and their average. Right: the exact transmission against the constant T_0.

The TE polarization transmits less at large angles and the TM polarization transmits more, up to the pseudo-Brewster angle. Their average is within 6% of T_0 up to 75°. Therefore, the constant T_0 replaces the Fresnel equations.

< 10 ms
for the map on the whole body, on one GPU, from 1 to 100 GHz

1.03
law/FDTD for 4 $\mathrm{cm^2}$ APD at 7 GHz, three-direction average

3 Absorption on the whole body



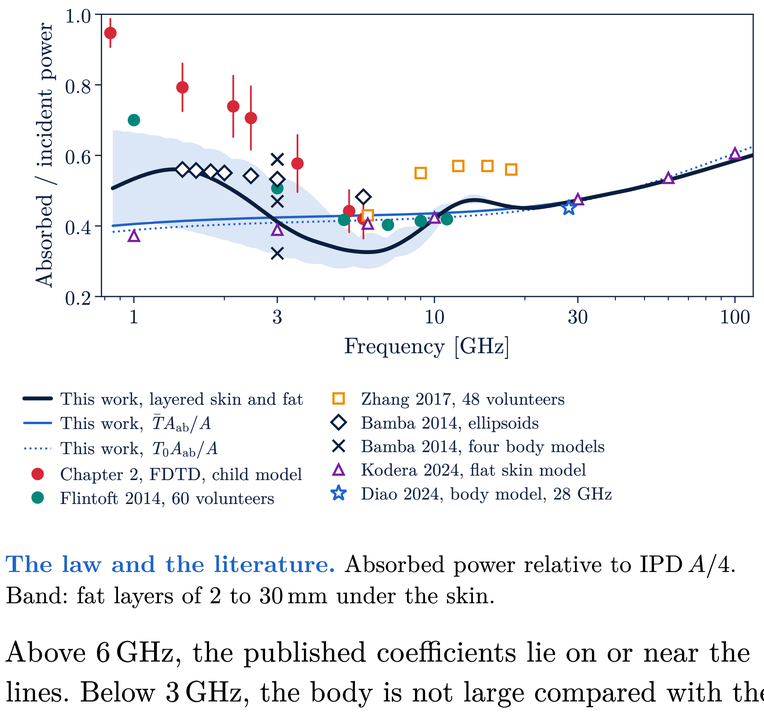
The cover shows the coherent form of this law. The colors are the absorbed power density on the six-year-old model, for an antenna array that focuses on the user at 10 GHz (scalar field, free space, relative scale). Each map is a matrix-vector product on a mesh of 23 826 triangles.

4 Whole-body absorbed power

Summed over the body and averaged over all directions of arrival, the law becomes

$$\langle P_{\mathrm{abs}} \rangle = \mathrm{IPD}\; \bar{T}\, \frac{A_{\mathrm{ab}}}{4},$$

with $\bar{T}$ the transmission averaged over the angle and A_{ab} the absorbing area. Body parts shadow each other, so A_{ab} is 86.5% of the skin area A of the six-year-old model.



The law and the literature. Absorbed power relative to IPD $A/4$. Band: fat layers of 2 to 30 mm under the skin.

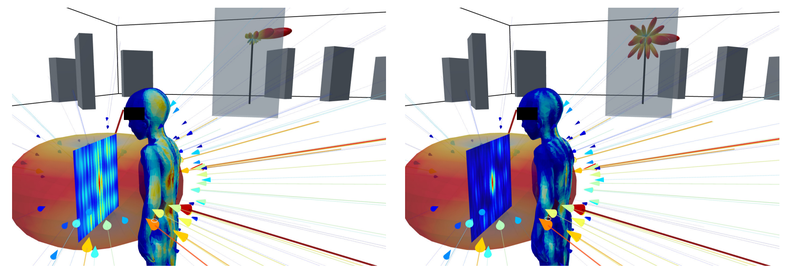
Above 6 GHz, the published coefficients lie on or near the lines. Below 3 GHz, the body is not large compared with the wavelength, and the FDTD values are higher. At 5.8 GHz, the ratio of the law to FDTD is 1.012 for the whole body.

5 Exposure-constrained beamforming

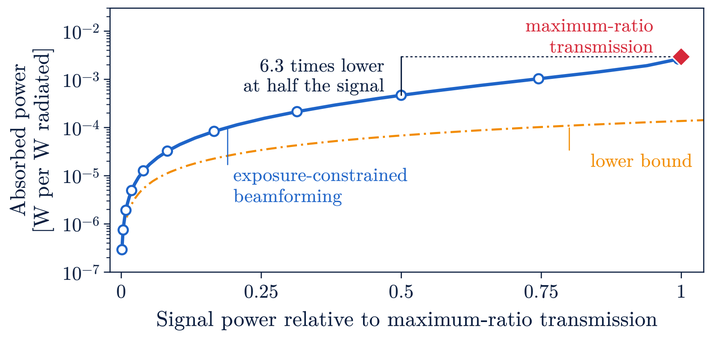
A base station sends from many elements with weights $\mathbf{x}$. With the phase of every ray included, the absorbed power and the best weights are

$$P_{\mathrm{abs}} = \mathbf{x}^{\mathsf{H}} \mathbf{Q}\, \mathbf{x}, \qquad \mathbf{x}_{\mathrm{opt}} \propto (\lambda \mathbf{Q} + \nu \mathbf{I})^{-1} \mathbf{h}^*,$$

with $\mathbf{Q}$ the exposure matrix of the body, $\mathbf{h}$ the channel to the device, and λ, ν the multipliers of the exposure and power limits.



Same signal at the device. Left: maximum-ratio transmission. Right: exposure-constrained beamforming. Colors: APD on the body.



Signal against absorbed power for an adult model in a factory hall. At half the signal power, the median reduction over 27 648 simulated cases from 8 to 100 GHz is 5.29. Experimental validation of the coherent operator is future work.

6 Conclusions

- Above 6 GHz, the absorbed power density is a function of body geometry and skin transmission.
- Without fitted parameters, the direction-averaged law agrees with FDTD within 3% and with published measurements on 108 volunteers.
- With phase, the exposure matrix is part of the precoder calculation.
- The law is for a plane wave from a distant source. In Chapter 6, Huygens-box wavelets are used and the predicted fields are compared with measurements.

References

[1] R. Wydaeghe, L. Martens, G. Vermeeren, E. Tanghe, and W. Joseph, "Closed-form absorbed-power dosimetry from 1 to 100 GHz," manuscript submitted to *IEEE Trans. Antennas Propag.*, 2026. [2] R. Wydaeghe, L. Martens, G. Vermeeren, E. Tanghe, and W. Joseph, "Exposure-constrained beamforming with a closed-form body absorption operator," manuscript submitted to *IEEE Trans. Wireless Commun.*, 2026. [3] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, 2020.

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All publications

imec waves — GHENT UNIVERSITY

Validation by measurement and exposure on walks through ten cities

Robin Wydaeghe, Arno Moerman, Olivier Caytan, Sergei Shikhantsov, Günter Vermeeren, Emmeric Tanghe, Hendrik Rogier, Sam Lemey, Piet Demeester, and Wout Joseph

WAVES and IDLab, Department of Information Technology, Ghent University – imec, Belgium

2 Full-wave reference | 3 Indoor hybrid method | 4 Outdoor hybrid method | 5 Closed-form dosimetry | 6 Measurements and cities

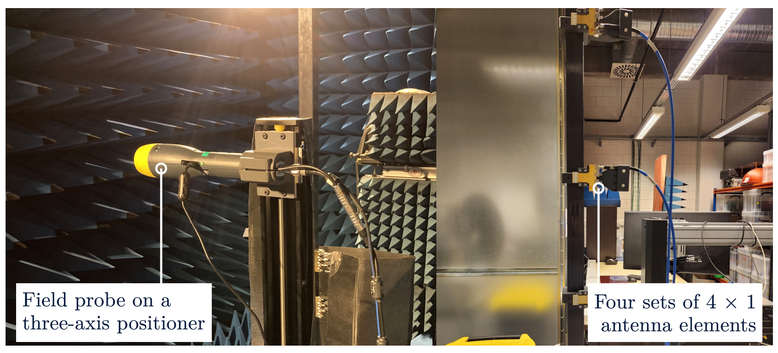
Along a line through a measured hot-spot, the field prediction has a 17% normalized mean absolute error. A digital twin of a stairwell predicts the interference pattern on a plane that was held out of its calibration. Across ten city routes, the highest median whole-body exposure is 14 times the lowest.

1 Question

Chapters 2 to 5 compare their methods with other simulations. How close are the measured and simulated fields? What is the exposure in a city where transmitter positions are unknown?

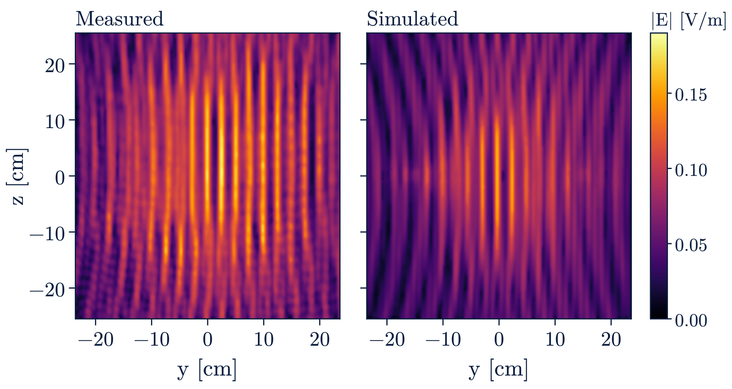
Scale	Frequency	Field from	Exposure from
Anechoic room	26 GHz	four antenna sets	none (field only)
Stairwell	28 GHz	ray tracing in a twin	law of Chapter 5
Ten cities	15 GHz	adjoint ray tracing	law of Chapter 5

2 Hot-spot in an anechoic room



Setup at 26 GHz. Phase shifters set the phase of four groups of four elements, so that all 16 add in phase at a point 62 cm away.

The probe scans 50 cm by 50 cm in steps of 3.33 mm, which takes 50 hours. The simulation sums four spherical waves, one per set, with the simulated set patterns and measured amplitudes, as in Chapter 4.



Electric field in the scan plane. Both maps have the wide region of the four beams, the fringes and the peak at the center.

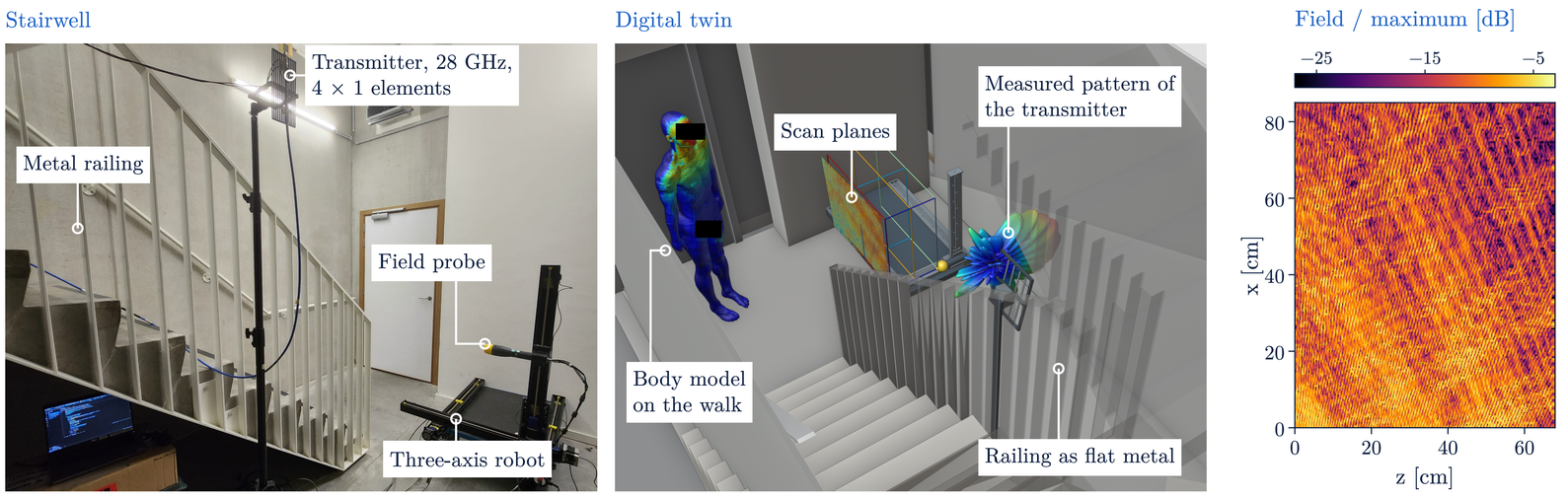
	Measured	Simulated
Peak field	0.19 V/m	0.17 V/m
Width of the central peak	0.93 cm	0.94 cm
Normalized mean absolute error	17% ± 10% (0.65 dB)	

Values are along the horizontal line through the center. The higher measured field on the right is attributed to scattering by the 48.5 cm probe, omitted from the simulation.

54 dB
below the basic restriction for the milliwatt source in the stairwell, least favorable calibration

314 s
ray and body calculation for 163 points in ten cities, on one A6000 GPU

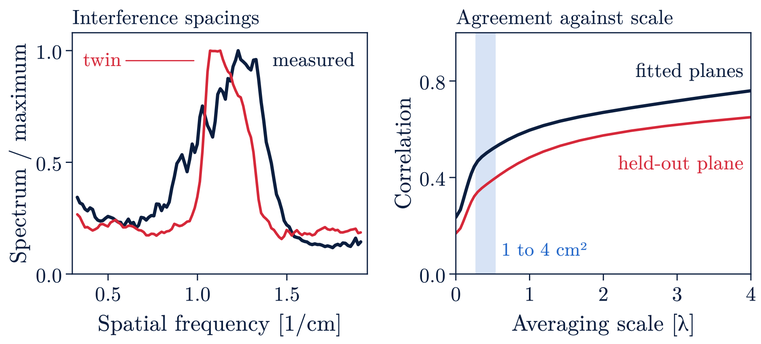
3 Stairwell and digital twin at 28 GHz



Left: a robot moves the probe over five planes in 31 hours. **Center:** the twin is built from the architectural model of the building. Ten pose and eight material parameters are calibrated. **Right:** the plane that was held out of the calibration.

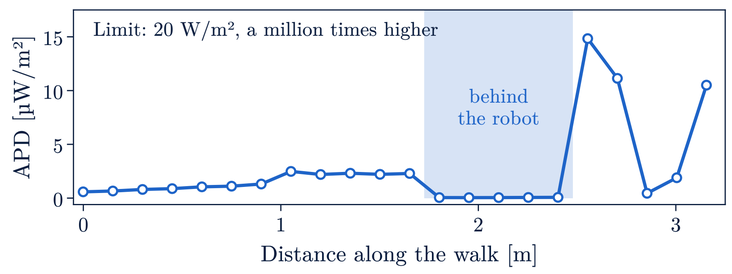
4 Prediction of a held-out plane

The probe measures only the field magnitude. We calibrate the twin on three planes and test it on the fourth, holding out each plane in turn.



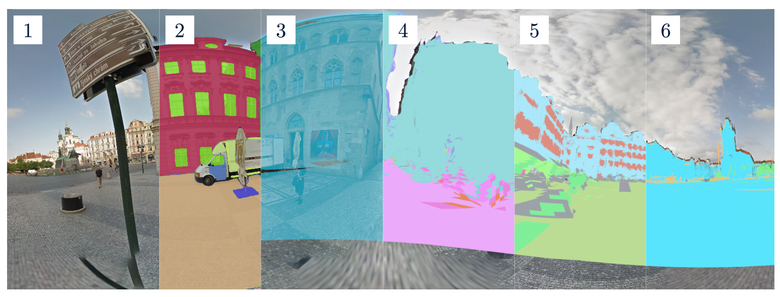
Held-out plane. Left: spectrum of the field along the scan lines. Right: correlation after averaging over a Gaussian window. Band: averaging areas of the ICNIRP guidelines.

Across four held-out planes, beat-spectrum correlation is 0.55 to 0.79. On this plane, pointwise correlation is 0.17 before averaging and 0.65 after averaging. The largest error is due to the railing's grating response.



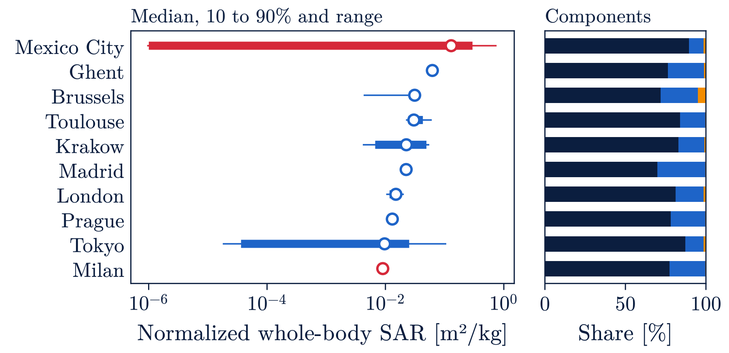
Absorbed power density over 4 cm² on a walk toward the transmitter, which radiates milliwatts. The Chapter 5 law uses the twin's field on a Huygens box. Calculation time is 31 s for 22 positions.

5 Ten cities at 15 GHz



Prague, Old Town Square. 1 street image, 2 object labels, 3 city mesh, 4 combined objects, 5 material labels, 6 input of the ray tracer.

Materials on visible mesh faces are assigned from street images. Unseen faces have a default material. Hypothetical sources are uniform along visible rooflines. The cost of receiver-to-source ray tracing is independent of source count.



Whole-body specific absorption rate (SAR) on ten routes, per unit of transmitter density and power. Right: direct (dark), specular (blue) and diffuse (amber) shares.

Direct paths are the largest component at 156 of 157 line-of-sight points. Six shadowed points receive only diffuse power. The factor of 14 depends on source placement, geometry and materials.

6 Conclusions

- The normalized mean absolute error of the hybrid method is 17% along a line through the measured hot-spot.
- A twin calibrated on magnitudes predicts averaged fields better than point values, and the limits apply to averages.
- The calculation time for ten cities is about five minutes. Outdoor measurement validation is future work.
- The models omit the probe, the robot and the grating response of the railing. Each case uses a single frequency and body model.

References

[1] R. Wydaeghe *et al.*, "New hybrid ray-tracing/FDTD for EMF exposure in 6G networks using semantically classified Google Earth photogrammetry with measurement validation," in *Proc. EuCAP*, Glasgow, 2024. [2] R. Wydaeghe *et al.*, "Holographic phase retrieval of RF-EMFs for human exposure assessment using fine 3D electric field measurements in a real environment from a beamforming 28 GHz antenna," in *Proc. EuCAP*, Stockholm, 2025. [3] R. Wydaeghe *et al.*, "Digital twin calibrated from phaseless 28 GHz measurement scans for indoor exposure assessment," manuscript submitted to *IEEE Antennas Wireless Propag. Lett.* [4] R. Wydaeghe *et al.*, "Human-centric 6G RF-EMF exposure with AI-assisted digital twins in ten cities," manuscript submitted to *IEEE Open J. Commun. Soc.*

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All publications

imec waves wireless, acoustics, environment & expert systems

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