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.

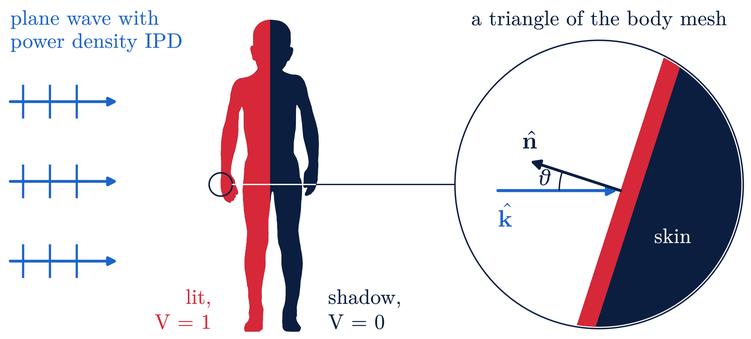
1 Question

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

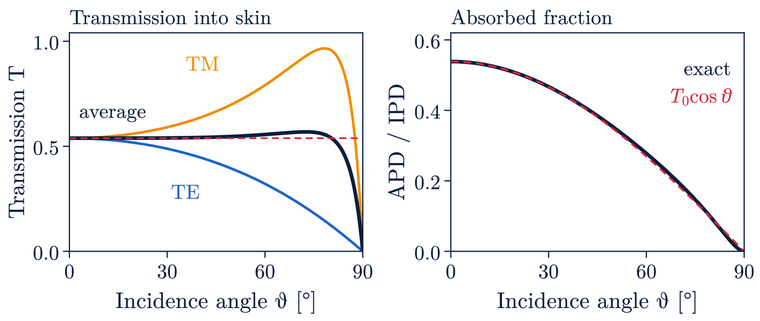


A plane wave on the body mesh. Every triangle has a normal $\hat{\mathbf{n}}$. The wave arrives along $\hat{\mathbf{k}}$ at the angle θ.

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.



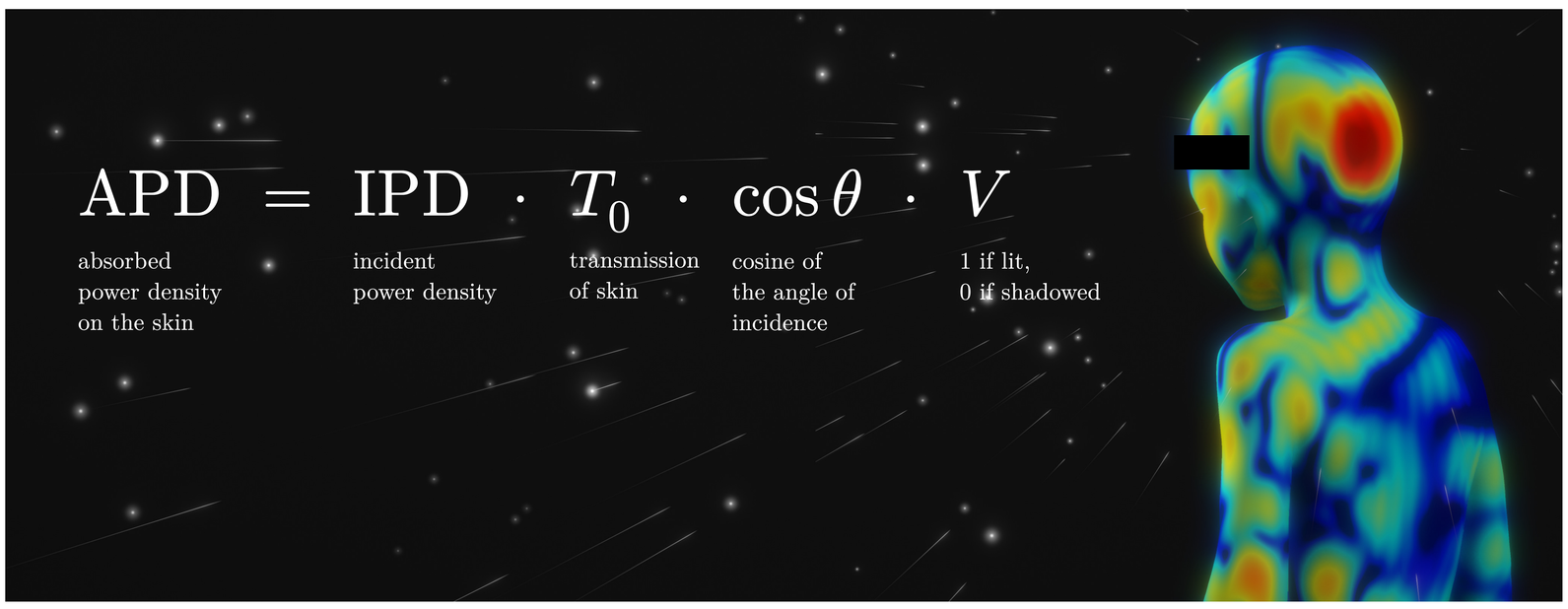
Skin at 28 GHz, $\tilde{n} = 4.49 - 1.79\mathrm{i}$ and $T_0 = 0.54$. Left: both polarizations and their average. Right: the exact transmission against the constant T_0.

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



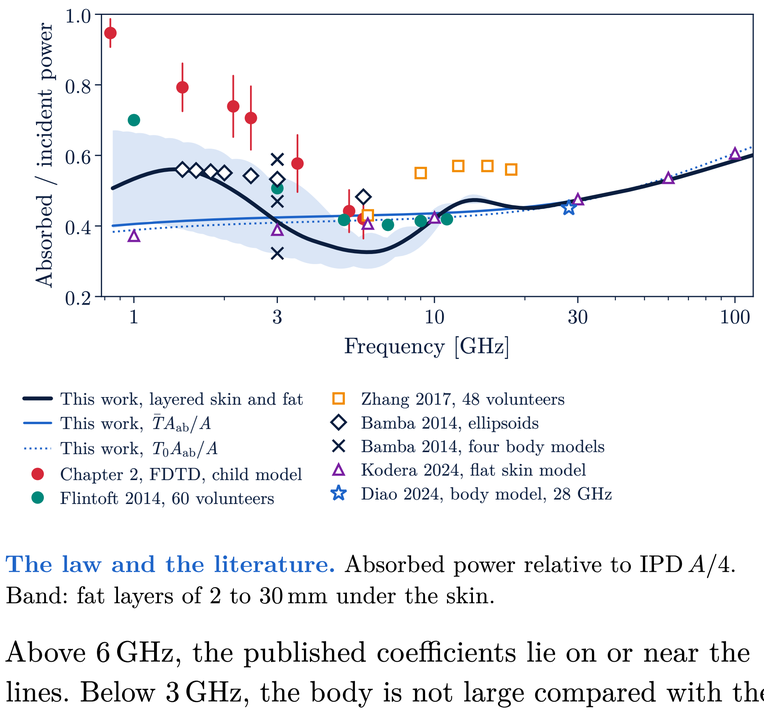
The cover shows the coherent form of this law. The colors are the absorbed power density on the six-year-old model, for an antenna array that focuses on the user at 10 GHz (scalar field, free space, relative scale). Each map is a matrix-vector product on a mesh of 23 826 triangles.

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.

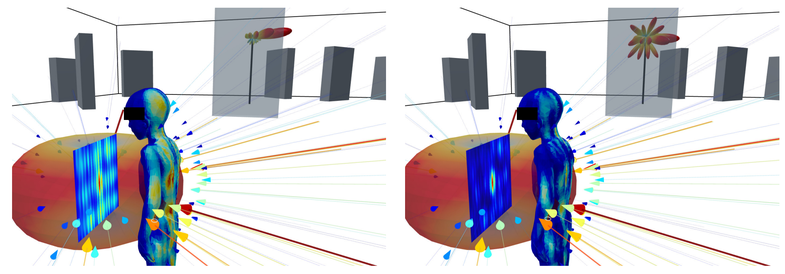
Above 6 GHz, the published coefficients lie on or near the lines. Below 3 GHz, the body is not large compared with the wavelength, and the FDTD values are higher. At 5.8 GHz, the ratio of the law to FDTD is 1.012 for the whole body.

5 Exposure-constrained beamforming

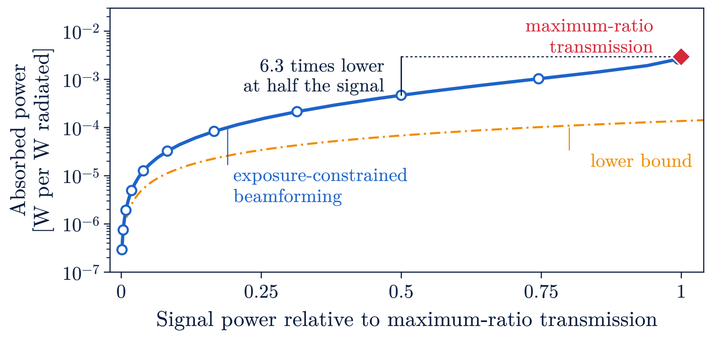
A base station sends from many elements with weights $\mathbf{x}$. With the phase of every ray included, the absorbed power and the best weights are

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

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.

Acknowledgement

This research was done in the WAVES research group of Ghent University and imec. The FDTD reference data are from the GOLIAT project, funded by the European Union's Horizon Europe programme under grant agreement No. 101057262.

All publications

imec waves — GHENT UNIVERSITY