Accelerating mmWave exposure simulations and the OUTREACH idea to industry

Robin Wydaeghe[1, 2], Erdem Ofli[3], Stefan Benkler[3], Guillermo Del Castillo[3], Sergei Shikhantsov[1, 2], Emmeric Tanghe[1, 2], Günter Vermeeren[1, 2], Luc Martens[1, 2], Niels Kuster[2, 3, 4] and Wout Joseph[1, 2]
[1]WAVES, Department of Information Technology at Ghent University, Ghent, Belgium
[2]Interuniversity Microelectronics Centre (IMEC), Leuven, Belgium
[3]ZMT Zurich MedTech AG, Zurich, Switzerland
[4]The Foundation for Research on Information Technologies in Society (IT'IS) Foundation, Zurich, Switzerland
[5]Department of Information Technology and Electrical Engineering, Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland
BioEM 2024, Crete, Greece, June 16-21, 2024

Number of words in the summary: 208 of the 250 allowed.

Number of words in the main text: 2700 of the approximately 2500 allowed.

Summary

This paper first presents techniques to improve the accuracy and efficiency of Radio-Frequency-Electromagnetic Field (RF-EMF) human exposure simulations. The efficiency of a coated dielectric layered skin model applied to a human head is examined for the first time. A new method to efficiently interface with Huygens boxes yields a 16-fold speed increase at 28 GHz. In total, a 64-fold increase is obtained in exposure assessment speed for a 6-minute walk in New York City. A growing population is concerned about health effects of 5G and 6G. While simulation studies with a "worst-case" methodology answer this, an important knowledge gap in literature remains for the layman's simple question: "how much exposure do I *realistically* experience in daily life from 5G?" To enable comprehensive end-to-end simulations, our OUTREACH (OUTdoor Realistic Exposure Assessment for next-generation Cellular networks on Humans) idea aims to collaborate with industrial partners to share accurate data, including e.g. real smartphone radiation patterns, real base station antenna patterns, and more. This is described in the second section of the paper. The goal and feasibility of the idea are outlined in a short survey. Then, a case is made for industrial and governmental partners to share data securely. Support will be garnered among experts at the BioEM 2024 conference.

Introduction

The fifth (5G) and sixth (6G) generations of cellular networks feature order of magnitude increases in antenna density and frequency. A portion of the population is concerned these could result in adverse health effects, sparking deployment stops, protests and general worry. However, no conclusive evidence exists that Electromagnetic Fields (EMFs) from 5G Base Stations (BSs) can exceed the maxima set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Between the transmitting of EMFs from the BS and the absorption in the human body, simulation studies conduct their analysis in a "worst-case" scenario at each step, making assumptions about other parts of the radio channel. There is a gap in the current literature on real daily exposure from EMFs with comprehensive end-to-end simulations. Nevertheless, the findings would interest both concerned citizens and policy-makers due to 5G and 6G's novelty. Also, fully integrated simulations enable EMF-aware network-planning and characterize wavelength-sized "hotspots": regions of increased EMF shaped by the BS technology, the propagation environment and the user [1].

Comprehensive end-to-end simulations can be divided consecutively into the scenario, propagation, hybridization and exposure step [1]. For the scenario step, the following data must be available. First, the 3D location and orientation of every BS in an area emitting 5G and 6G Radio-Frequency (RF) radiation. Second, the antenna pattern of all antenna elements inside the BS and its implementation of massive multiple-input multiple-output (MaMIMO). Third, a 3D mesh of the propagation environment accurate within the scale of the simulation's wavelength. Fourth, realistic electromagnetic material parameters for each polygon in the mesh. In the propagation step, a performant ray-tracer or state-of-the-art map-based deterministic radio channel generator yields the EMFs directed in a beam towards the user. In the hybridization step, the far-fields are evaluated in the near-field of the user, while coupling the channel to the UE. Access to a real antenna pattern and CAD model of a smartphone would significantly improve this channel coupling [1]. In the final exposure step, an anatomically correct 3D human model suitable for mmWave frequencies must be accessible. The exposure levels are then evaluated after performing a finite-difference time-domain (FDTD) simulation. Ultimately, end-to-end simulations with minimal assumptions are mainly hampered by a lack of available data and high computational costs.

Through industry outreach, the OUTREACH idea aims to close these data gaps for the outdoor downlink case with 5G and 6G networks. The acronym OUTREACH stands for "OUTdoor Realistic Exposure Assessment for next-generation Cellular networks on Humans". This paper is divided into two parts: results on acceleration of the exposure step, and an overview of our idea. In the first part, the fruits of a research stay with the company ZMT Zurich MedTech AG and the research institute IT'IS Foundation are presented. The efficiency of the hybridization and exposure step at high frequencies is drastically improved through several techniques. For this research collaboration, an unavailable 3D human model for mmWave frequencies was provided. In the second part, the feasibility of OUTREACH is first established based on a short survey of recent advancements in academic research and industry. Then, a case is made for industrial and governmental partners to securely share the required data. Finally, experts will be polled at the Third International Conference on Bioelectromagnetics (BioEM 2024) to garner support within the academic community.

First results: accelerating exposure simulations at mmWave frequencies

This section presents findings from a research stay with ZMT and the IT'IS Foundation, funded by the Research Foundation – Flanders (FWO). The results enabled and sparked the OUTREACH idea.

Using coated dielectric layered skin models

The EMF penetration depth in human tissue at 30 GHz is 0.92 mm [2]. ICNIRP's latest RF-EMF exposure metric for frequencies above 6 GHz is the surface absorbed power density (S_{ab}). Accurately computing S_{ab} requires an over-resolved voxeling of the human phantom, increasing the computational requirements significantly. In 2021, Christ *et al* from the IT'IS Foundation confirmed the suitability of using layered skin models for dosimetry studies [3]. In 2022, the *coated dielectric mmWave material* was incorporated into ZMT's 7th release of Sim4Life. A human head phantom with the coating was provided. This phantom is homogenous with a size of 10 kB, much lower than the commonly used heterogeneous phantoms with a size of up to 400 MB. The latter's epidermis dermis layer is 19 kB, double-sided and contains imperfections. For these reasons, S_{ab} is computed more than **twice** as fast and while maintaining accuracy.

New method for the efficient use of Huygens' boxes

In 2023, a Huygens box was first used in favor of a set of plane waves to improve the accuracy of the hybridization step in our end-to-end pipeline [1]. When the incident fields are evaluated only on the sides of the Huygens box, the computational costs scale quadratically instead of cubically when evaluated volumetrically. However, Sim4Life cannot import these on the surface of the box alone. The following method solves this issue.

In Sim4Life, the incident field can be defined either by a volumetric ASCII file or by the output EMFs of a primary simulation. By choosing the latter, a binary representation of the secondary simulation's Huygens fields are obtained after an arbitrary dummy simulation. By choosing identical grids, the actual fields only need to be replaced, circumventing any field interpolations. The incident EMFs are evaluated on the appropriate Yee-grid. To ensure proper field averaging in Sim4Life, this is done only from 3 cells before to 3 cells beyond the Huygens interface. No dielectric media can be present here. Values deeper inside the box have no effect. Similarly, every EMF vector component parallel to the faces can be omitted, as they do not contribute to the equivalent surface currents. The interfacial fields are loaded using the low-level HDF5 API. The import is approximately **16 times** faster than the previous approach at 28 GHz, increasing linearly beyond this frequency.

Overview of acceleration techniques

Up to 5000 FDTD simulations are required to compute the RF-EMF exposure along a six minute walk. As the computational costs scale to the fourth power with frequency, the hybridization and exposure step present computational challenges for mmWaves. Some techniques that most improve performance are compiled in the following.

- First, the domain size should be reduced whenever possible, as they influence computational costs cubically. The results from a simulation with crude resolution indicate regions where the exposure is highest. The region of highest exposure can then be computed at the desired resolution. The same can be applied for evaluating S_{ab}, where the surface discretization parameter has the largest impact on performance.
- Second, Sim4Life features the possibility to run on a high-performance cluster. Concurrent jobs on the latest NVIDIA CUDA cards can increase the computational budget by orders of magnitude. Lossy 8x compression should be applied on downloaded and uploaded field data, as the error is acceptable for our purposes.
- Third, weak time-wise convergence is sufficient because the induced error falls within the margin of error already present in the pipeline. Point field sensors detect convergence more efficiently than volumetric field sensor.
- Fourth, the phantom's skin layer absorbs the vast majority of power at mmWave frequencies. As detailed above, using a homogeneous mmWave phantom avoids high memory consumption and retains accuracy.
- Finally, when computing the exposure of several incident field on the same grid, the voxels on that grid should be cached, such that their evaluation is not repeated between runs.

The exact increase in efficiency of each technique depends on the frequency and a large number of other factors. We consider a simple 6 minute walk in NYC's World Trade Center as described in [1]. In Figure 1 (a), the outdoor environment is shown, with the exposure S_{ab} plotted as a function of time at 28 GHz in Figure 1 (b). For the 3160 positions, the exposure step took 18 hours before the optimizations and about 16 minutes after them.

OUTREACH: overview, feasibility and outreach

Goal and feasibility

The goal of our idea OUTREACH is to provide a clear and accurate answer to the layman's question "how much exposure do I experience in daily life from 5G in my city?". The answer can be expressed statistically as a percentage of the ICNIRP reference levels and basic restrictions and as function of location, e.g., as a heatmap. The idea is illustrated in Figure 2. Accuracy and coverage should be maximized to obtain convincing results to individuals and policy-makers. The scope can be extended to sub-THz 6G applications such as distributed MaMIMO systems.

In the following section, a short survey details areas where realistic data is most needed, with examples of partners that could provide them. Recent advancements in industry and government are highlighted**,** which enable realistic end-to-end simulations. A working pipeline is published alongside this paper that combines all data currently freely available [1]. This demonstrates feasibility of the OUTREACH idea as every critical step has fallback options.

Survey of available data

The exact locations and orientations of 5G BSs is often not easily available to the public on city or country scales. First, crowd-sourcing based services such as OpenCellID, CellMapper, Combain use signal strength triangulation to offer an estimate of their locations. However, the accuracy is insufficient, in particular for regions with sparse data. Second, some governmental institutions keep a record in the cadastre of an antenna's location (and other details) when it is registered by an operator. One example is the United States' FCC Antenna Structure Registration. However, the registration is incomplete because it is not always mandatory. Data is more thorough in European countries such as France, Belgium, and the Netherlands. To achieve high coverage on a continental scale, collaboration is necessary as not all API's are always accessible to the public. Finally, large mobile operators (e.g. Verizon, AT&T, Deutsche Telekom, Vodafone, …) presumably keep track of every BS's detail in their whole network. This data could be shared for the OUTREACH idea.

As Björnson *et al* wrote in 2019: "The development of MaMIMO communication technology is now in the hands of the product departments of companies such as Ericsson, Huawei, Nokia, etc." [4] Commercial BSs are now available for in the highest Frequency Range 2 (FR2) with a large number of elements in MaMIMO arrangements. In academia, this is typically modeled with an arbitrary arrangement of dipole or patch antennas. 3GPP [5] provides a more detailed description of these antenna patterns but they are ultimately not real patterns. It also does not account for inter-element interaction. The exact MIMO configuration, power control, duty cycles, and precoding schemes are unknown while being crucial to the amount of RF-EMF exposure. Therefore, any antenna pattern from a BS supplier would significantly improve the realism of the simulations.

The same is true for the UE, where a smartphone will be used. A generic smartphone model, simple antenna pattern and arbitrary orientation is often used in academic research. The antenna pattern of the receiving 5G module, which is now ubiquitous in smartphones, has an influence on the radio channel at the UE side. The model of the smartphone itself also has an influence on the scattering of the near-field onto the human. Thus, obtaining any of the above data from a smartphone (e.g. Apple, Samsung, Xiaomi, …) or component (e.g. Qualcomm) manufacturer would improve the realism significantly.

Databases with 3D meshes of outdoor environments exist with varying degrees of Level of Detail (LoD) and coverage. First, Open Street Maps (OSM) provides a freely licensed map consisting of buildings, streets and many other features. The coverage is expansive, in particular for Europe and the United States. The LoD of buildings varies from footprints with height information (2.5D) to custom-modeled buildings (3D). However, wavelength-sized details are not always resolved and 3D foliage is absent. Therefore, the radio channel can exhibit a lack of multi-path diversity. The strength of OSM is in its semantic nature, such that material parameters can be assigned by feature type without the use of machine learning. Second, photogrammetry data with wavelength-sized precision is available using for example LiDAR scanning technology. The coverage however does not extend past the city scale. Finally, several companies also offer wide-coverage and high-LoD maps with 3D buildings. The 3D layer is typically generated from aerial survey imagery and therefore not completely semantically labeled. In some cases, the mesh has accuracies down to several centimeters. The maps also usually include real foliage. Google Maps, Bing Maps and ArcGIS are examples of key industrial players in this space. In recent years, most of these (notably Google in 2023) provide an API with low-cost access. While the data can be streamed in, legal restrictions apply to offline use. Cooperation to share the data is essential to accurately compute the channel in end-to-end simulations.

Radio channel models can be classified as either stochastic or deterministic. Based on a comparative survey of stochastic models [6], a hybrid of the map-based QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) v2.8 [7] with the mmMAGIC [8] model integrates the most amount of software features. A characterization of the propagation environment type with Line-of-Sight/Non-Line-of-Sight detection is sufficient to model the channel. The model calibration is ultimately based on measurements, improving the level of realism. Deterministic models have the potential to be even more accurate. Full ray-tracing however requires accurate, heterogeneous knowledge of the constitutive material parameters, which remains scarce [9]. A differential ray-tracer can be used to optimize the material parameters to a reference signal by means of gradient descent. NVIDIA released *Sionna* in 2023, the first radio propagation differentiable ray-tracer, which also takes full advantage of their GPU's [10]. We intend to use this open-source software with stochastic modeling as fallback.

As described in the first results, data of a human phantom with a coated dielectric skin model is essential to accurately and efficiently compute S_{ab} at mmWave frequencies. Therefore, the exposure step in our new OUTREACH idea is already completed.

The case for data sharing from industry

The required data contains proprietary intellectual property from the company or its stakeholders, causing reluctance. However, sharing data exceptionally for the OUTREACH idea affords companies the opportunity to appease individuals and policy-makers of 5G deployment. Moreover, they contribute academically to cutting edge research, as the results are unparalleled within the EMF exposure literature. RF-EMF exposure experts at BioEM 2024 will be polled to support this claim and express their opinion. Finally, all data will be kept inaccessible to other partners and contractually safeguarded.

Acknowledgments

This work was supported by the ERC through "ATTO: A New Concept for Ultrahigh Capacity Wireless Networks" under Grant 695495 and Methusalem through "SHAPE: Next Generation Wireless Networks". The research stay was supported by the FWO through file number K215823N.

References

[1] R. Wydaeghe *et al.*, "Characterization of EMF hotspots for realistic exposure assessment in end-to-end simulations using a hybrid QuaDRiGa/FDTD tool," in Third International Conference on Bioelectromagnetics, Crete, Greece, *unpublished*.

[2] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)", *Health Phys*, 118(00):000–000, 2020.

[3] A. Christ *et al.*, "Reflection Properties of the Human Skin From 40 to 110GHz: A Confirmation Study," in Bioelectromagnetics, 42: 562-574, Jul. 2021, doi:10.1002/bem.22362.

[4] E. Bjornson *et al.*, "Massive MIMO is a reality—What is next?", *Digital Signal Processing*, vol. 94, pp. 3-20, Nov. 2019, doi: 10.1016/j.dsp.2019.06.007.

[5] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (Release 17)," TR 38.901 V17.0.0, Mar. 2022, sec. 7.3.

[6] C.-X. Wang, J. Bian, J. Sun, W. Zhang, and M. Zhang, "A Survey of 5G Channel Measurements and Models," in IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 3142-3168, 2018.

[7] S. Jaeckel *et al.*, "QuaDRiGa - Quasi Deterministic Radio Channel Generator, User Manual and Documentation", Fraunhofer Heinrich Hertz Institute, Tech. Rep. v2.8.1, 2024.

[8] M. Tercero *et al.*, "5G systems: The mmMAGIC project perspective on use cases and challenges between 6–100 GHz," 2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Doha, Qatar, 2016, pp. 200-205.

[9] D. He *et al.*, "The Design and Applications of High-Performance Ray-Tracing Simulation Platform for 5G and Beyond Wireless Communications: A Tutorial," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 10-27, 2019.

[10] J. Hoydis *et al.*, "Sionna RT: Differentiable Ray Tracing for Radio Propagation Modeling", arXiv preprint, version 2, Jul. 2023.

Figures

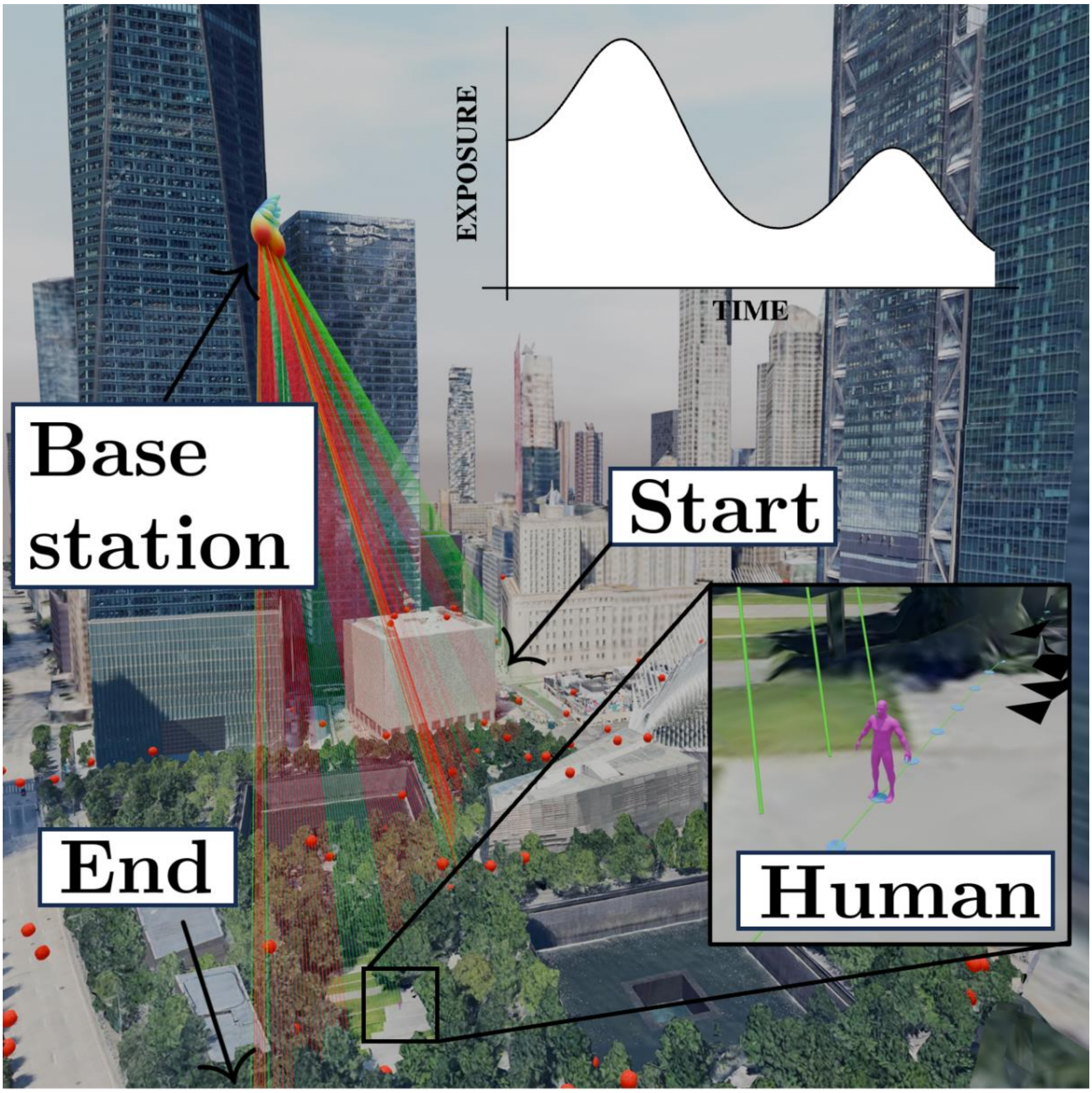

Figure 1: A 5G MIMO BS on One World Trade Center exposes a human to RF-EMF along a 6-minute walk in New York City. The red dots represent (insufficiently accurate) locations from OpenCellID's database of BS. Both the BS and UE have arbitrary radiation patterns. The QuaDRiGa channel model generates data based on, e.g., LOS/NLOS data as indicated by the green and red lines.

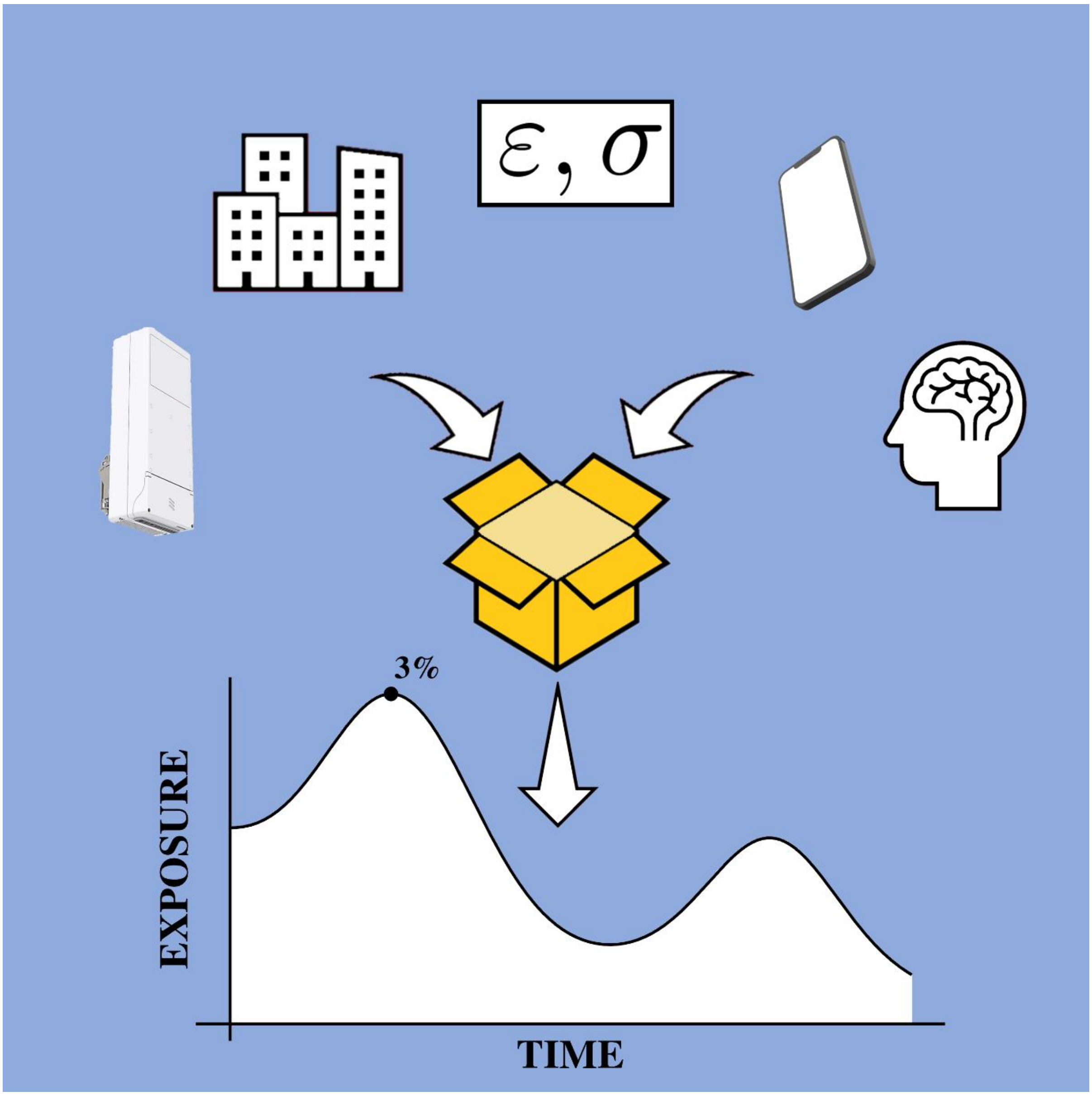

Figure 2: A simple illustration of the OUTREACH idea. Some of the required data from industry is shown in the top half of the image. These should be securely assembled and utilized in an end-to-end simulator to produce the daily realistic exposure experienced as a function of time. The result is the exposure metric as a percentage of ICNIRP's EMF safety guidelines as a function of time along a realistic walk.