

A thermal map of a human head and torso, showing heat distribution in shades of blue, green, yellow, and red. The head is on the right, and the torso is on the left. The background is black with white stars and streaks, suggesting a space theme.

Hybrid Computational Methods for 6G Exposure Assessment

Robin Wydaeghe

Doctoral dissertation submitted to obtain the academic degree of
Doctor of Engineering Physics

Supervisors

Prof. Wout Joseph, PhD - Prof. Emmeric Tanghe, PhD
Department of Information Technology
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*Dedicated to my godfather, Koen Wydaeghe.
I hope you would have been proud.*

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I can see this becoming a long section.

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Robin Wydaeghe
Ghent, October 2026

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List of Acronyms

3GPP 3rd Generation Partnership Project.

5G Fifth-Generation.

6G Sixth-Generation.

ALARA As Low as Reasonably Achievable.

AoA Angle of Arrival.

AP Access Point.

APD Absorbed Power Density.

APN Access-Point Network.

BS Base Station.

CDF Cumulative Distribution Function.

CFL Courant–Friedrichs–Lewy.

CF-MaMIMO Cell-Free Massive Multiple-Input Multiple-Output.

CIR Channel Impulse Response.

CPW Cells per Wavelength.

CSF Cerebrospinal Fluid.

DMaMIMO Distributed Massive Multiple-Input Multiple-Output.

DoA Direction of Arrival.

ECBF Exposure-Constrained Beamforming.

EIRP Equivalent Isotropic Radiated Power.

EMF Electromagnetic Field.

FCC Federal Communications Commission.

FDTD Finite-Difference Time-Domain.

FR1 Frequency Range 1.

FR2 Frequency Range 2.

FR3 Frequency Range 3.

FWHM Full Width at Half Maximum.

GELU Gaussian Error Linear Unit.

GEV Generalized Eigenvalue.

GSCM Geometry-Based Stochastic Channel Model.

HPC High-Performance Computing.

ICNIRP International Commission on Non-Ionizing Radiation Protection.

InF-SH Indoor Factory with Sparse Clutter and a High Base Station.

IPD Incident Power Density.

LBS Last-Bounce Scatterer.

LoD Level of Detail.

LOS Line of Sight.

LSF Large-Scale Fading.

LSP Large-Scale Parameter.

MaMIMO Massive Multiple-Input Multiple-Output.

MIDA Multimodal Imaging-Based Detailed Anatomical Model.

mmWave Millimeter-Wave.

MRT Maximum Ratio Transmission.

MVDR Minimum-Variance Distortionless Response.

NLOS Non-Line of Sight.

NYC New York City.

P/P Prominence-to-Peak.

PEC Perfect Electric Conductor.

PML Perfectly Matched Layer.

QCQP Quadratically Constrained Quadratic Program.

QuaDRiGa Quasi-Deterministic Radio Channel Generator.

RF Radio Frequency.

RF-EMF Radio-Frequency Electromagnetic Field.

RS Radio Stripe.

RT Ray Tracing.

SAR Specific Absorption Rate.

SBR Shooting and Bouncing Rays.

SNR Signal-to-Noise Ratio.

SOTA State of the Art.

SSF Small-Scale Fading.

TDMA Time-Division Multiple Access.

TE Transverse Electric.

TF/SF Total-Field/Scattered-Field.

TM Transverse Magnetic.

UE User Equipment.

UPML Uniaxial Perfectly Matched Layer.

URA Uniform Rectangular Array.

ViP Virtual Population.

wbSAR Whole-Body Averaged Specific Absorption Rate.

Nederlandse samenvatting

Draadloze netwerken van de vijfde generatie (5G) bedienen wereldwijd miljarden gebruikers, en de standaardisatie van de zesde generatie (6G) is aan de gang. Elke generatie gebruikt hogere frequenties, van de sub-6-GHz-banden van 4G naar de millimetergolfbanden (mmWave) boven 24 GHz en de bovenste middenband rond 6–24 GHz. De architectuur van basisstations is veranderd van enkele antennes naar massieve Multiple-Input-Multiple-Output-antennestelsels (massive MIMO), bundelvorming en gedistribueerde of celvrije configuraties waarin veel toegangspunten samen elke gebruiker bedienen. Regelgevers, gezondheidsinstanties en het publiek vragen hoeveel Radio-Frequente Elektromagnetische-Veldblootstelling (RF-EMV-blootstelling) een persoon in echte netwerken ontvangt. Epidemiologische studies hebben realistische blootstellingsschattingen nodig, omdat worstcasewaarden de dagelijkse blootstelling met ordes van grootte overschatten.

De richtlijnen van de International Commission on Non-Ionizing Radiation Protection (ICNIRP) uit 2020 definiëren twee niveaus van limieten. Basisrestricties zijn vastgelegd op grootheden binnenin het lichaam: het Specifiek Absorptietempo (SAR) onder 6 GHz en de Geabsorbeerde Vermogensdichtheid (APD) boven 6 GHz. Referentieniveaus zijn vastgelegd op het invallende veld buiten het lichaam en zijn afgeleid uit de basisrestricties onder worstcaseaannames. De belangrijkste uitdaging voor de bepaling van blootstelling in realistische omgevingen is het bereik van ruimtelijke schalen. De propagatieomgeving strekt zich uit over ongeveer 100 m, het menselijk lichaam is ongeveer 1 m lang, en de absorberende huidlaag is minder dan 1 mm dik bij mmWave-frequenties. Geen enkele rekenmethode bestrijkt deze vijf ordes van grootte tegen een aanvaardbare rekenkost. Dit proefschrift bouwt een reeks van rekenmethoden, van vollediggolfsimulatie tot uitdrukkingen in gesloten vorm, die algemeenheid inruilt voor snelheid. Elke methode gebruikt een van twee interfaces om het volledige elektromagnetische veld (amplitude, fase, richting en polarisatie) van de omgeving naar het lichaam over te dragen: een verreveldpadlijst of een Huygens-doois.

In Hoofdstuk 2 worden de referentiesimulaties uitgevoerd. Het hoofdstuk gebruikt 550 Eindige-Differentie-Tijddomein-simulaties (FDTD) over vier anatomische fantomen (twee volwassenen en twee kinderen), 15 frequenties van 450 MHz tot 26 GHz, en zowel omgevings- als zelfgeïnduceerde blootstelling. De belangrijkste bevinding is dat conformiteit met de referentieniveaus niet altijd de conformiteit met de basisrestricties garandeert. De absorptie in kinderen overschrijdt de lichaamsbasisrestrictie nabij 2140 MHz (tot 145% voor het zesjarige kindfantoom), terwijl volwassen fantomen onder 82% blijven. Bij focusering door faseaanpassing,

met een totale vermogensdichtheid van 10 W/m^2 over de invallende componenten, overschrijdt de absorptie in alle vier fantomen de lokale basisrestrictie bij 3500 MHz (131–158%). Het hoofdstuk geeft ook de eerste verreveldvergelijking van APD bij kinder- en volwassen fantomen over 7–15 GHz. Deze resultaten zijn beperkt tot vier fantomen in staande houding, zonder enige invloed van de specifieke draadloze omgeving.

In Hoofdstuk 3 wordt de hybride stralentracering/FDTD-methode uitgebreid naar 28 GHz en naar de APD zoals vereist door de ICNIRP-2020-richtlijnen. Stralentracering levert het locatiespecifieke meerpadskanaal op industriële schaal, en FDTD berekent de absorptie in de dunne huidlaag van een anatomisch fantoom. In een industriële binnenomgeving levert gedistribueerde massive MIMO een factor 2–3 lagere blootstelling op dan een gecolloceerde opstelling. De hoogste blootstelling over alle configuraties is 4% van de ICNIRP-limieten. Basisrestrictiegrootheden zijn 5–10 dB onder hun limieten wanneer de referentieniveaus op hun limieten staan.

In Hoofdstuk 4 wordt de hybride methode uitgebreid naar buitenopstellingen met celvrije massive MIMO bij 28 GHz, met 3D-stadsmodellen op basis van fotogrammetrie van Helsinki en New York. Een stochastische kanaalgenerator wordt gecombineerd met locatiespecifieke stralentracering om ruimtelijk consistente kanalen langs stedelijke voetgangersroutes te produceren. De celvrije architectuur vermindert het dynamisch bereik van de blootstelling met ongeveer 20 dB ten opzichte van een gecolloceerde opstelling. De maximale blootstelling is lager dan 0,05% van de ICNIRP-limieten voor 320 W totaal uitgezonden vermogen. De bundelvormings-hot-spot voegt 12 dB toe bovenop de grootschalige bundelvormingsversterking en is ongeveer een halve golflengte breed. De FDTD-absorptieberekening kost echter meerdere uren per evaluatie, en deze kost neemt toe met de vierde macht van de frequentie.

In Hoofdstuk 5 wordt de FDTD-absorptieberekening vervangen door twee uitdrukkingen in gesloten vorm, afgeleid uit de Fresneltransmissietheorie en de integraalgeometrie. De incoherente wet ontbindt het totaal geabsorbeerd lichaamsvermogen in de invallende vermogensdichtheid, een fluxgewogen Fresneltransmissie en een lichaamsvormfactor. De coherente uitbreiding drukt het geabsorbeerd vermogen onder een voorcodering uit als een kwadratische vorm, samengesteld uit dezelfde paden van de stralentracering als het communicatiekanaal. Beide formuleringen komen overeen met FDTD binnen de 7% onzekerheid op de weefseldielektrische eigenschappen. Een volledige lichaamskaart duurt minder dan 10 ms op een Grafische Verwerkingseenheid (GPU). Dit is te vergelijken met uren voor FDTD bij mmWave-frequenties. Blootstellingsbeperkte Bundelvorming (ECBF) is afgeleid uit de coherente operator: bij de helft van het signaalvermogen bij Maximale-Verhoudingstransmissie (MRT) vermindert ECBF het mediaan totaal geabsorbeerd lichaamsvermogen met een factor 5,29 over 746 496 lichaamskaarten.

In Hoofdstuk 6 worden de methoden gevalideerd aan de hand van metingen in een anechoïsche kamer en een binnenomgeving, en toegepast op stadsschaal. In de anechoïsche kamer bij 26 GHz reproduceert de hybride stralentracering/FDTD-methode de grootte van de elektrische-veldcomponent langs de meetprobe rond een

gebundelde hot-spot, met 17% genormaliseerde gemiddelde absolute fout. In de trappenhal bij 28 GHz voorspelt een digitale tweeling, gekalibreerd op basis van faseloze robotskans, achtergehouden interferentiepatronen met zweefspectrumcorrelatie (Pearson) van +0,55 tot +0,79. De hoogste berekende APD ligt meer dan 54 dB onder de ICNIRP-2020-basisrestrictie voor het grote publiek. Op stadsschaal wordt de routegebonden totale-lichaams-SAR berekend op 163 observatiepunten in tien steden bij 15 GHz, met behulp van adjuncte stralentracering, beeldgeïnformeerde materiaaltoewijzing op basis van straatpanorama's en de wet in gesloten vorm uit Hoofdstuk 5. De mediaan van de SAR per route verschilt met een factor 14 tussen steden. De berekening van alle tien routes samen duurt ongeveer vijf minuten op één enkele GPU.

Hoofdstuk 7 beantwoordt de vier onderzoeksvragen, vergelijkt de kost, de nauwkeurigheid en de toepasbaarheid van de methoden, en bespreekt de beperkingen en het toekomstig onderzoek. Het hoofdstuk geeft vijf richtingen voor toekomstig onderzoek, waaronder een buitenmeetcampagne voor validatie van de stadsschaalmethode, tijdsgemiddelde blootstellingsbeoordeling, blootstellingsbeperkte bundelvorming voor meerdere lichamen en blootstellingsstatistieken op populatieschaal.

De belangrijkste bevindingen over het gehele proefschrift zijn als volgt. Gedistribueerde en celvrije architecturen op basis van massive MIMO produceren een lagere piekblootstelling dan gecolloceerde opstellingen. Het verschil tussen referentieniveaus en basisrestricties hangt af van de frequentie, de lichaamsgeometrie en de meerpadsomgeving: bij kinderen en onder gefocusseerde belichting kan de absorptie de basisrestricties benaderen of overschrijden nabij 2140, 3500 en 7000 MHz. Elk realistisch scenario dat bestudeerd werd, ligt ver onder de ICNIRP-limieten. De methoden en gegevens uit dit proefschrift zijn beschikbaar voor conformiteitsbeoordeling, netwerkontwerp en epidemiologische studies. Het rekenpad van een draadloze opstelling naar de geabsorbeerde dosis in een menselijk lichaam is nu compleet: volledige golfsimulatie waar hoge nauwkeurigheid nodig is, gesloten vorm waar rekensnelheid nodig is, en gemeten waar nauwkeurige metingen en digitale tweelingen beschikbaar zijn.

English Summary

Fifth-generation (5G) wireless networks serve billions of users worldwide, and standardization of the sixth generation (6G) is under way. Each generation uses higher carrier frequencies, from the sub-6 GHz bands of 4G to the millimeter-wave (mmWave) bands above 24 GHz and the upper mid-band around 6–24 GHz. Base-station architectures have changed from single antennas to massive Multiple-Input Multiple-Output (MIMO) arrays, beamforming, and distributed or cell-free deployments in which many access points serve each user. Regulators, health agencies, and the public ask how much Radio-Frequency Electromagnetic Field (RF-EMF) exposure a person receives in real networks. Epidemiological studies need realistic exposure estimates, because worst-case values overestimate the daily exposure by orders of magnitude.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2020 guidelines define two tiers of limits. Basic restrictions are set on quantities inside the body: the Specific Absorption Rate (SAR) below 6 GHz and the Absorbed Power Density (APD) above 6 GHz. Reference levels are set on the incident field outside the body and are derived from the basic restrictions under worst-case assumptions. The main challenge for exposure assessment in realistic environments is the range of spatial scales. The propagation environment extends over roughly 100 m, the human body is about 1 m tall, and the absorbing skin layer is less than 1 mm thick at mmWave frequencies. No single computational method covers these five orders of magnitude at acceptable cost. This thesis builds a set of computational methods, from full-wave simulation to closed-form expressions, that balances generality for speed. Each method uses one of two interfaces to pass the full electromagnetic field (amplitude, phase, direction, and polarization) from the environment to the body: either a far-field path list or a Huygens box.

In Chapter 2, reference simulations are established from 550 Finite-Difference Time-Domain (FDTD) simulations across four anatomical phantoms (two adults, two children), 15 frequencies from 450 MHz to 26 GHz, and both environmental and auto-induced exposure. The main finding is that reference-level compliance does not always guarantee basic-restriction compliance. The absorption in children exceeds the whole-body basic restriction near 2140 MHz (up to 145% for the six-year-old child phantom) where adult phantoms remain below 82%. Under phase-only focusing at a total incident component power density of 10 W/m^2 , the absorption in all four phantoms exceeds the localized basic restriction at 3500 MHz (131–158%). The chapter also presents the first child–adult far-field APD comparison across 7–15 GHz. These results are limited to four phantoms in a standing posture, without

any influence from the specific wireless environment.

In Chapter 3, the hybrid ray-tracing/FDTD method is extended to 28 GHz and to the APD as required by the ICNIRP 2020 guidelines. Ray tracing provides the site-specific multipath channel at industrial scale, and FDTD computes the absorption in the thin skin layer of an anatomical phantom. In an indoor industrial environment, distributed massive MIMO produces a factor of 2–3 lower exposure than a collocated deployment. The highest exposure found across all configurations is 4% of the ICNIRP limits. Basic-restriction quantities are 5–10 dB below their limits when reference levels are at their limits.

In Chapter 4, the hybrid method is extended to outdoor cell-free massive MIMO at 28 GHz, using photogrammetric 3D city models of Helsinki and New York. A stochastic channel generator is combined with site-specific ray tracing to produce spatially consistent channels along urban pedestrian routes. The cell-free architecture reduces the exposure dynamic range by approximately 20 dB compared to a collocated deployment. The maximum exposure is below 0.05% of the ICNIRP limits for 320 W total radiated power. The beamforming hot-spot adds 12 dB on top of the large-scale beamforming gain and is roughly half a wavelength wide. However, the FDTD body-absorption computation costs several hours per evaluation, and this cost increases as the fourth power of frequency.

In Chapter 5, the FDTD body-absorption computation is replaced by two closed-form expressions derived from Fresnel transmission theory and integral geometry. The incoherent law factors the whole-body absorbed power into the incident power density, a flux-weighted Fresnel transmission, and a body shape factor. The coherent extension expresses the absorbed power under a precoder as a quadratic form, assembled from the same ray-traced paths that determine the communication channel. Both formulations match FDTD within the 7% tissue-dielectric uncertainty. A full-body map takes less than 10 ms on a Graphics Processing Unit (GPU), compared to hours for FDTD at mmWave frequencies. Exposure-Constrained Beamforming (ECBF) is derived from the coherent operator: at half the Maximum-Ratio Transmission (MRT) signal power, ECBF reduces the median whole-body absorbed power by a factor of 5.29 across 746 496 full-body maps.

In Chapter 6, the methods are validated against measurements in an anechoic chamber and a real indoor environment, and applied at city scale. In the anechoic chamber at 26 GHz, the hybrid ray-tracing/FDTD method reproduces the probe-axis electric-field magnitude around a beamformed hot-spot with 17% normalized mean absolute error. In the indoor stairwell at 28 GHz, a digital twin calibrated from phaseless robotic scans predicts unseen interference patterns with beat-spectrum Pearson correlation +0.55 to +0.79. The maximum computed APD is more than 54 dB below the ICNIRP 2020 general-public basic restriction. At city scale, route-level whole-body SAR is computed at 163 observation points across ten cities at 15 GHz, using adjoint ray tracing, image-informed material mapping from street-level panoramas, and the closed-form law from Chapter 5. Route-median SAR differs by a factor of 14 between cities. The ten-route calculation takes about five minutes on a single GPU.

Chapter 7 answers the four research questions, compares cost, accuracy, and applicability of the methods, and discusses limitations and future work. The chapter presents five directions for future research, including an outdoor measurement campaign to validate the city-scale method, time-averaged exposure assessment, multi-body exposure-constrained beamforming, and population-scale exposure statistics.

The main findings across the thesis are as follows. Distributed and cell-free massive MIMO architectures produce lower peak exposure than collocated deployments. The gap between reference levels and basic restrictions depends on frequency, body geometry, and the multipath environment: absorption in children and under focused illumination can approach or exceed the basic restrictions near 2140, 3500, and 7000 MHz. Every realistic scenario studied is far below the ICNIRP limits. The methods and data produced in this thesis are available for compliance assessment, network design, and epidemiological studies. The computational path from a wireless deployment to the absorbed dose in a human body is now complete: full-wave where high accuracy is needed, closed-form where computational speed is needed, and measured where accurate measurements and digital twins are available.

1

Introduction

“DON’T PANIC!”

— Douglas Adams

1.1 Context and motivation

Fifth-generation (5G) wireless networks have reached global deployment scale, serving more than two billion subscribers in over one hundred countries [1]. The ITU-R framework for sixth-generation (6G), named IMT-2030, was published in 2023 [2]. Standardization is underway [1, 3], with deployment targeted for the early 2030s. These networks target fiber-like wireless connectivity with extreme capacity, sub-millisecond latency, high reliability, dense device support, and low power consumption [4, 5]. Each generation introduces spectrum above 6 GHz. Current 5G deployments operate primarily in Frequency Range 1 (FR1) (0.45–6 GHz). Frequency Range 3 (FR3) (7–15 GHz) is under standardization as a centimeter-wave band that combines moderate bandwidth with more favorable propagation than millimeter-wave (mmWave) [3]. Frequency Range 2 (FR2) (24–52.6 GHz) provides the mmWave capacity layer, deployed in some markets, notably the United States and South Korea [1]. Each step upward in frequency changes how radio waves interact with the human body, so exposure assessment must be revisited with each generation.

The higher frequencies come with a change in antenna architecture. Massive Multiple-Input Multiple-Output (MaMIMO) uses a large antenna array to serve multiple users simultaneously on the same time-frequency resource, which increases

spectral efficiency. The array concentrates radiated energy into narrow beams directed toward individual users, replacing the broad radiation patterns of earlier base stations (BSs). Network densification places access points closer to the served population. Distributed and cell-free architectures extend this principle by spreading antenna panels across a coverage area rather than concentrating them on a single collocated tower [6, 7]. These changes have a direct consequence for exposure assessment. Energy is no longer broadcast uniformly but directed toward individual users, which creates a distinction between *auto-induced* exposure of the served user and *environmental* exposure of bystanders. Therefore, the spatial distribution of exposure depends on the deployment architecture, not only on the total transmitted power.

A recurring question from regulators, public-health agencies, and the general public is how much radio-frequency electromagnetic field (RF-EMF) exposure a person realistically receives from these networks. Deployments of new BSs have been delayed or blocked in response to public concern in several countries [8]. Epidemiological studies require realistic exposure estimates as inputs, and spectrum regulators must weigh compliance with exposure guidelines when approving new frequency allocations. The question cannot be answered by worst-case analysis alone. Worst-case values are needed for product certification and guideline verification, but they overestimate the exposure a person encounters in daily life by orders of magnitude. Answering the realistic question requires methods that combine propagation in the wireless environment with absorption in the human body under representative conditions.

In 2026, the World Health Assembly urged Member States to strengthen national monitoring of public, occupational and patient exposure to ionizing and non-ionizing radiation, including electromagnetic fields [9, para. 1(4)].

The regulatory framework is set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2020 guidelines [10]. These guidelines define basic restrictions on quantities measured inside the body and reference levels on quantities measured outside it. Below 6 GHz, the local basic restriction is the spatial-peak specific absorption rate (SAR), a mass-averaged absorbed-power metric. Above 6 GHz, the basic restriction changes to the surface-averaged absorbed power density (APD), which quantifies power absorbed per unit area at the body surface. This transition reflects the physical fact that absorption becomes increasingly superficial with rising frequency. Compliance with a reference level is intended to guarantee compliance with the corresponding basic restriction. However, the reference-level derivation relies on worst-case assumptions about the body geometry, so the correspondence between the two levels is not exact [11, 12]. Reference-level compliance does not always ensure basic-restriction compliance. This inconsistency is one of the technical questions examined in this thesis.

The core technical obstacle is the range of spatial scales involved. The wireless channel extends over hundreds of meters to kilometers, spanning buildings, streets, and open areas. Absorption is determined by fields that must be resolved on the millimeter geometry of the human body. At mmWave frequencies, the penetration depth in tissue falls below one millimeter, so the absorbing layer is thinner than a

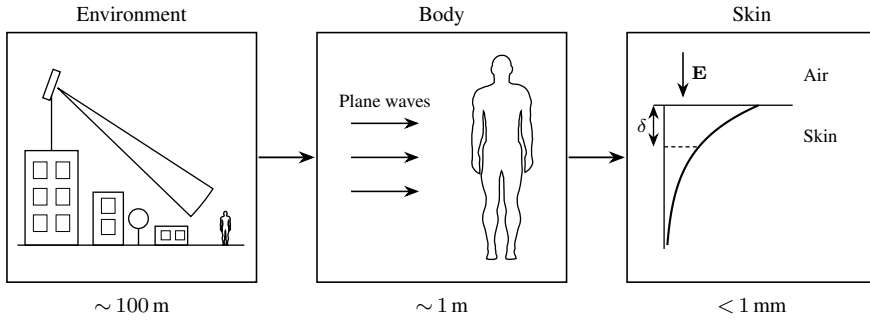


Figure 1.1: Three spatial scales of the exposure problem. Left: the wireless environment, where a base station illuminates a person. Centre: the body, on which the field arrives as plane waves. Right: the skin, in which the electric field E decays with depth. The penetration depth is δ . Arrows between panels mark the magnification.

single wavelength. A brute-force full-wave simulation that resolves the environment and the human body together would require on the order of 10^{12} computational cells¹ [13]. No single simulation method in current use spans these scales at acceptable computational cost.

Fig. 1.1 illustrates the three-scale structure of the problem: an environment at the hundred-meter scale contains a human body at the one-meter scale, and absorption occurs within a thin surface layer at the sub-millimeter scale.

This dissertation **develops and validates a progression of computational methods for realistic exposure assessment** of next-generation wireless networks. The progression moves from accurate but expensive full-wave simulations to fast closed-form expressions, with hybrid methods connecting the two. Each method is designed around a specific part of the scale gap identified above, and the methods form a ladder that trades generality for computational reach. The remainder of this chapter introduces the electromagnetic, technological, and dosimetric background needed to formulate this problem precisely, followed by the research questions, contributions, and chapter outline in Section 1.6.

1.2 Electromagnetic propagation fundamentals

1.2.1 Maxwell's equations and wave propagation

Electromagnetic wave propagation is governed by Maxwell's equations [14]. In a source-free medium characterized by its permittivity ϵ , permeability μ , and

¹A $10 \times 10 \times 3$ m³ room at 0.5 mm resolution (≈ 23 cells per wavelength at 26 GHz) gives $2 \times 10^4 \times 2 \times 10^4 \times 6 \times 10^3 \approx 2.4 \times 10^{12}$ cells. The body alone, at the finer 0.1 mm step needed to resolve the penetration depth, requires $\sim 10^{10}$ cells (Section 1.5.1).

conductivity σ , the two curl equations take the time-harmonic form

$$\nabla \times \mathbf{E} = -j\omega\mu \mathbf{H}, \quad \nabla \times \mathbf{H} = j\omega\varepsilon \mathbf{E} + \sigma \mathbf{E}, \quad (1.1)$$

where $\mathbf{E}$ is the electric field vector in volts per meter, $\mathbf{H}$ is the magnetic field vector in amperes per meter, $\omega = 2\pi f$ is the angular frequency in radians per second, j is the imaginary unit, ε is the electric permittivity of the medium in farads per meter, μ is the magnetic permeability in henrys per meter, and σ is the electric conductivity in siemens per meter. The first equation is Faraday's law: a time-varying magnetic field produces a circulating electric field. The second is the Ampère–Maxwell law: the electric field drives both displacement current and conduction current.

In free space, these equations have plane-wave solutions. The electric field of a plane wave has the form

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_0 e^{-j\mathbf{k} \cdot \mathbf{r}}, \quad (1.2)$$

where $\mathbf{E}_0$ is a constant complex amplitude vector, $\mathbf{k} = (2\pi/\lambda) \hat{\mathbf{k}}$ is the wave vector with magnitude $2\pi/\lambda$ and unit propagation direction $\hat{\mathbf{k}}$, $\lambda = c/f$ is the wavelength, c is the speed of light, and $\mathbf{r}$ is the position vector. The polarization of the wave is the orientation of $\mathbf{E}_0$ in the plane perpendicular to $\hat{\mathbf{k}}$. A point source radiates spherical wavefronts that expand with distance. At sufficiently large distances, the curvature becomes negligible over body-scale dimensions and the field is locally planar. This is why the far-field decomposition of Section 1.2.2 yields plane-wave components.

The power carried by the wave per unit area is given by the time-averaged Poynting vector, whose magnitude defines the incident power density (S_{inc})

$$S_{\text{inc}} = \frac{|\mathbf{E}|^2}{2\eta}, \quad (1.3)$$

where $\eta = \sqrt{\mu/\varepsilon}$ is the wave impedance of the medium. In free space, $\eta \approx 377 \Omega$. Incident power density (IPD) is the primary quantity that connects the propagation environment to the human body throughout this thesis. It appears in every chapter as the field quantity that is either simulated, measured, or analytically related to absorption.

When a plane wave enters a lossy medium such as biological tissue, the fields decay exponentially with depth. The characteristic penetration distance is the penetration depth, at which the power density has fallen to $1/e$ of its surface value,

$$\delta = \frac{1}{2\omega} \sqrt{\frac{2}{\mu\varepsilon'}} \left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon'}\right)^2} - 1 \right]^{-1/2}, \quad (1.4)$$

where ε' is the real part of the permittivity. In biological tissue, the permittivity and conductivity are frequency-dependent and are characterized by the Gabriel parametric model [15].

Fig. 1.2 shows the penetration depth of dry skin as a function of frequency, with the FR1, FR3, and FR2 bands marked. At 1 GHz the penetration depth is

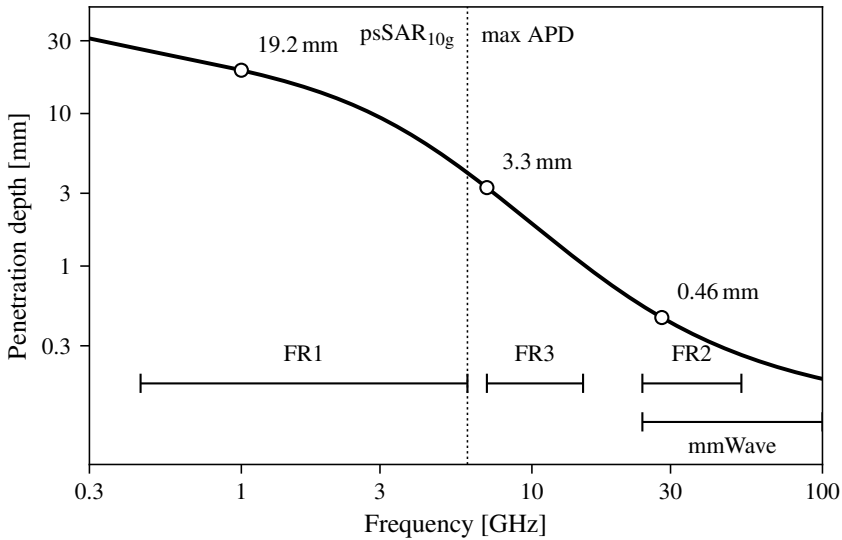


Figure 1.2: Power penetration depth in dry skin as a function of frequency, computed from the Gabriel parametric model [15]. Open circles mark the values quoted in the text. The dotted line marks 6 GHz, where the local ICNIRP basic restriction changes from the 10 g spatial-peak SAR (psSAR_{10g}) to the maximum APD. Brackets mark the FR1, FR3, FR2, and mmWave bands.

approximately 20 mm, so incident power penetrates into deeper tissue layers. At 28 GHz it is below 0.5 mm, and nearly all absorption occurs at the body surface. This transition from volumetric to superficial absorption is the physical basis for the change in the local basic restriction from spatial-peak SAR to maximum APD above 6 GHz.

1.2.2 Antennas and field regions

An antenna transforms a guided electromagnetic wave on a transmission line into a radiated wave in space [14]. Its radiation pattern describes the angular distribution of radiated power, and the directivity quantifies how strongly the pattern is concentrated relative to an isotropic radiator. The gain is the product of the directivity and the radiation efficiency, which accounts for ohmic losses in the antenna structure. The Equivalent Isotropic Radiated Power (EIRP) is the product of the accepted input power and the antenna gain and represents the power that an isotropic antenna would need to produce the same peak power density. A single-element antenna has a relatively broad pattern. An array of N elements can steer and shape the pattern electronically, and the array gain scales with N . A 64-element array at 28 GHz concentrates its power into a beam about ten degrees wide (Fig. 1.3). This concentration is the physical foundation of beamforming in

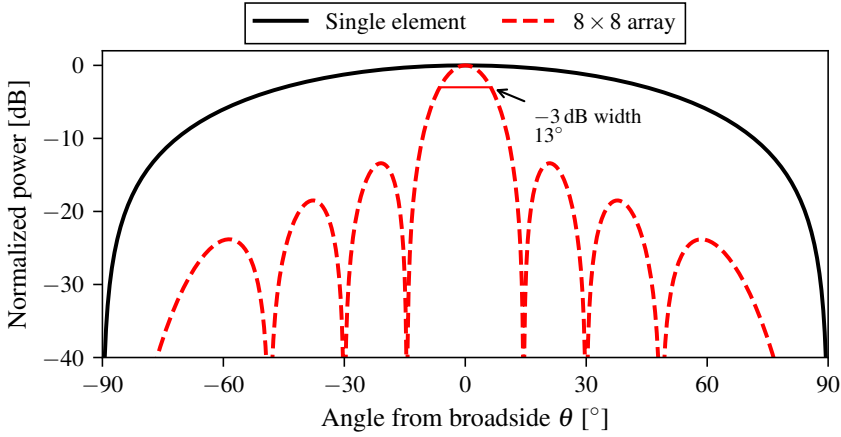


Figure 1.3: Normalized power pattern of a single element and of a uniform 8×8 array with half-wavelength spacing at 28 GHz, principal-plane cut at broadside. The array narrows the half-power beamwidth from 90° to 13° and redistributes the remaining power into side lobes.

MaMIMO systems, introduced in Section 1.3.

The field radiated by an antenna has a different spatial structure at different distances. Close to the antenna, in the reactive near field, the electric and magnetic fields do not behave as a plane wave, and their ratio is not the free-space impedance. Beyond the reactive region lies the radiating near field, where the angular pattern varies with distance. The far field begins at approximately the Fraunhofer distance [14, 16]

$$d_F = \frac{2D^2}{\lambda}, \quad (1.5)$$

where D is the largest dimension of the antenna aperture and λ is the wavelength. For the 64-element array of Fig. 1.3, whose largest dimension is its 5 cm diagonal, the Fraunhofer distance at 28 GHz is roughly 0.5 m. Beyond this distance the field can be approximated as a superposition of plane waves, which simplifies both propagation modeling and exposure assessment.

The near-field and far-field distinction has direct consequences for exposure assessment. A handheld device operates within centimeters of the head or hand, well inside the reactive near field of the device antenna. In this region the coupling between antenna and body is strong and must be characterized by full-wave simulation of the combined antenna-body system. A BS antenna, by contrast, is typically mounted several meters above ground, and most of the served population stands in its far field. In the far field the incident field can be decomposed into a superposition of plane waves, each with a well-defined direction and polarization. This decomposition is used by every method in this thesis that couples propagation to the body. Chapters 3 and 4 pass plane-wave coefficients through a Huygens

surface, and the closed-form laws of Chapter 5 integrate over plane-wave directions analytically.

Uplink exposure from a nearby handset is generally higher locally, while environmental downlink exposure can continue between handset transmissions. Lee *et al.* [17] found whole-brain SAR from downlink exposure comparable to or higher than uplink exposure in many of their South Korean mobile-network scenarios. This thesis considers downlink exposure from base stations. Near-field exposure from a user's device is outside its scope.

1.2.3 Reflection, transmission, and diffraction

When a plane wave impinges on a planar interface between two media, part of the wave is reflected and part is transmitted. The Fresnel coefficients give the amplitude ratios as functions of the incidence angle θ_i and the electromagnetic properties of the two media. The plane of incidence contains the incident direction and the surface normal (Fig. 1.4b). In a transverse electric (TE) polarized wave, the electric field is perpendicular to the plane of incidence. In a transverse magnetic (TM) polarized wave, it lies in that plane. For a TE wave incident on a medium with complex refractive index $\tilde{n}$, the amplitude reflection coefficient is

$$r_{\text{TE}} = \frac{\cos \theta_i - \sqrt{\tilde{n}^2 - \sin^2 \theta_i}}{\cos \theta_i + \sqrt{\tilde{n}^2 - \sin^2 \theta_i}}. \quad (1.6)$$

The corresponding expression for TM polarization has a Brewster angle at which the reflection vanishes for lossless dielectrics. On a lossy material such as biological tissue the reflection minimum shifts to a pseudo-Brewster angle and does not reach zero [18]. The power reflection coefficient $|r|^2$ of a tissue-like dielectric is plotted against incidence angle in Fig. 1.4a, with the pseudo-Brewster minimum annotated. This angular dependence of reflection, and therefore of absorption, is used directly in Chapter 5.

When a wave encounters an obstacle whose dimensions are comparable to the wavelength, diffraction occurs. The wavefront bends around edges and spreads into geometrical shadow regions. The Huygens–Fresnel principle provides a physical picture: every point on a wavefront acts as a source of secondary wavelets, and the diffracted field is the superposition of these secondary waves. This principle also underlies the Huygens surface, a closed surface on which the tangential electric and magnetic fields are recorded and then re-radiated to compute the field inside. The Huygens surface is one of the two interfaces between the propagation-scale and body-scale computations (Fig. 1.6a, Section 1.5.4) and is used in Chapters 3, 4, and 6. In the first two chapters, it hybridizes the field with Finite-Difference Time-Domain (FDTD). In Chapter 6, it hybridizes the field with the closed-form surface law of Chapter 5.

The balance between penetration and reflection changes with frequency. At sub-6 GHz frequencies, common building materials such as drywall and glass transmit a substantial fraction of the incident power, so indoor users receive outdoor

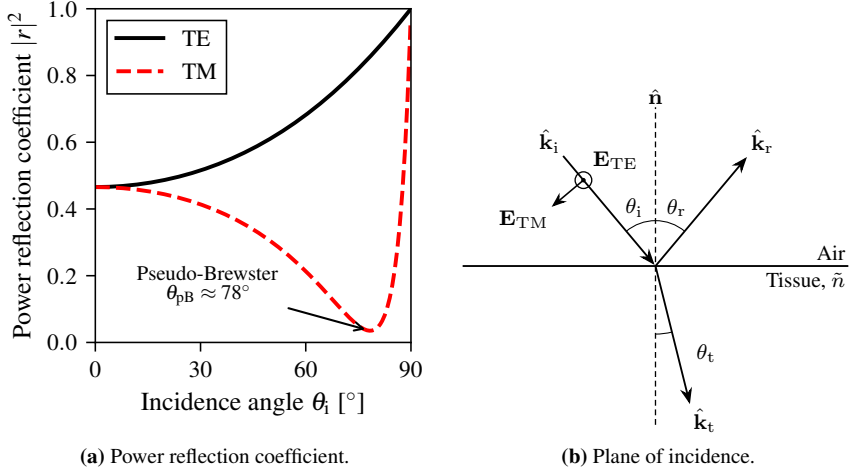


Figure 1.4: Reflection of a plane wave at a planar air/tissue interface. (a) Power reflection coefficient $|r|^2$ versus incidence angle for a tissue-like half-space ($\epsilon_r \approx 17$, $\sigma \approx 26$ S/m at 28 GHz, from [15]). The TM curve has a pseudo-Brewster minimum near 78° [18]. (b) The plane of incidence contains the incident, reflected and transmitted directions and the surface normal. The TE field is perpendicular to this plane, the TM field lies in it.

BS signals. At mmWave frequencies the same materials reflect or absorb most of the incident power; surface roughness also becomes comparable to the wavelength, redistributing energy away from the specular direction. The human body itself becomes an effective blocker. A 28 GHz campaign compared a full-body phantom with 17 subjects. The phantom showed about 14–15 dB of power loss in the pure shadow region with different types of clothing [19]. This frequency dependence explains several design choices in the thesis. The hybrid methods of Chapters 3 and 4 treat indoor and outdoor environments separately, and the closed-form laws of Chapter 5 model the body surface as the primary absorbing interface.

1.2.4 Multipath channels

In a real environment the signal arriving at a receiver is a superposition of waves that have traveled along different paths [16]. A direct line of sight (LOS) path, if it exists, carries the strongest signal. Additional paths arise from reflections off building facades, diffraction around edges, and scattering from rough surfaces and small objects. Each path has a specific attenuation, delay, direction of arrival, and direction of departure. The relative amplitudes and phases of these paths determine both the received signal strength and the local electromagnetic field pattern around a person. For exposure assessment, the multipath structure matters because it determines how power arrives at the body surface, from which directions, and with

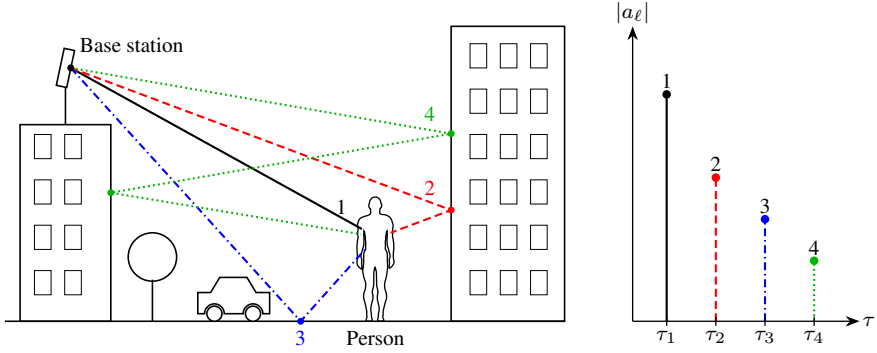


Figure 1.5: Multipath propagation in a street. A BS reaches a person through a LOS path (1), a reflection off a facade (2), a reflection off the ground (3), and two reflections off facades (4). Each path arrives from its own direction and forms one component of the CIR (right), drawn in the same colour and line style.

what angular spread. Fig. 1.5 shows a schematic street channel, in which each path is one term of the channel impulse response (CIR).

The multipath channel is described mathematically by the CIR, which expresses the channel as a sum of discrete components,

$$h(\tau) = \sum_{\ell=1}^L a_{\ell} e^{j\varphi_{\ell}} \delta(\tau - \tau_{\ell}), \quad (1.7)$$

where L is the number of resolvable paths, a_{ℓ} is the amplitude of the ℓ -th path, φ_{ℓ} is its phase, τ_{ℓ} is its delay, and $\delta(\cdot)$ is the Dirac delta function. Each path also carries a direction of arrival and a polarization state. In Fig. 1.5 the four paths reach the person from four different directions. These angular and polarization parameters are not captured by the scalar CIR but are retained by all computational methods in this thesis, because absorption depends on incidence angle and polarization (Sections 1.2.3 and 1.5). Each term in the sum corresponds to one path in Fig. 1.5. The CIR is the representation that every computational method in Section 1.5 ultimately produces or consumes. Ray tracing (RT) produces it deterministically from a three-dimensional scene. Stochastic channel models generate it statistically from a probability distribution. The hybrid methods of this thesis convert it into incident fields at a Huygens surface surrounding the body.

The path delays in the CIR set the relative phases of the multipath components at the carrier frequency. These phases must be retained when computing coherent absorption.

The superposition of multipath components causes the received field strength to vary spatially and temporally [16]. Large-scale fading describes the slow variation of mean power with distance, caused by path loss and shadowing from large obstacles. Small-scale fading describes rapid fluctuations over distances comparable

to the wavelength, caused by constructive and destructive interference among the multipath components. When many paths arrive with similar amplitude and uniformly distributed phase, the resulting field follows a Rayleigh distribution. When a dominant LOS path is present, the distribution becomes Rician. For exposure assessment, a critical distinction is whether the multipath components combine coherently or incoherently. In the incoherent case the total absorbed power is the sum of the individual path contributions. Throughout this thesis, a *hot-spot* is a local spatial maximum of a field or exposure quantity. A coherent hot-spot has a wavelength-scale concentration from constructive interference among phase-aligned paths. Coherent hot-spots have attracted increasing attention but remain underexplored [20–22]. This concept recurs throughout Chapters 3–5. The distinction between incoherent and coherent summation organizes the two parts of Chapter 5: the incoherent absorption law and its coherent extension.

1.3 Next-generation wireless technology

Operation at mmWave frequencies offers bandwidths of hundreds of MHz to several GHz per carrier, enabling the high data rates required by dense deployments and bandwidth-intensive applications. The trade-off is increased path loss, which scales with the square of the frequency for a fixed antenna aperture. At 28 GHz the free-space path loss over 100 m is approximately 30 dB higher than at 3.5 GHz for an isotropic radiator. This increase makes directional transmission necessary at mmWave frequencies. Antenna arrays with tens to hundreds of elements compensate the path loss by concentrating energy into beams that are a few degrees wide. The link budget is recovered, but the spatial distribution of radiated power differs from that of a conventional broadcast antenna.

FR3 (7–15 GHz) is an emerging compromise band for 6G that combines moderate bandwidth with propagation characteristics more favorable than mmWave [3]. Building penetration is still significant at these frequencies, and the required array sizes are smaller than at 28 GHz. From a dosimetric perspective, FR3 lies directly above the 6 GHz boundary at which the ICNIRP guidelines change the local basic restriction from spatial-peak SAR to maximum APD. Therefore, a system moving from FR1 into FR3 crosses the change in dosimetric quantity, even though neither the network geometry nor the anatomy changes abruptly. The penetration depth at 7 GHz is approximately 3 mm, so absorption is neither fully volumetric nor fully superficial. Existing studies tend to focus on either sub-6 GHz or 24 GHz and above, leaving this transitional band underserved. Chapter 2 addresses this gap with full-wave dosimetry results at frequencies between 7 and 15 GHz.

MaMIMO equips the BS with many more antenna elements than there are simultaneously served users [23]. A typical commercial 5G deployment uses 64 antenna elements and serves eight to sixteen users per time-frequency resource [24]. With knowledge of the downlink channel, the BS computes a precoding matrix that steers a separate beam toward each user. Under maximum ratio transmission (MRT) precoding the beam directed at one user delivers maximum power to that

user and creates interference toward others that averages out as the array grows [25]. The resulting spatial selectivity has two distinct effects on exposure. The served user receives a higher peak power density than under omnidirectional transmission, because the beam is concentrated. The average environmental exposure may be lower, because less power is radiated in directions where no user is present.

The spatial concentration of radiated power by beamforming creates a pattern of exposure that varies over space and time. When a BS serves a moving user, the beam tracks the user, and the exposure of any bystander at a fixed location is intermittent and depends on the traffic load. The peak incident power density on the served user can exceed the spatially averaged value by a factor that grows with the number of antenna elements. In a collocated deployment, where all elements are mounted on a single tower, the beams converge from a common direction and the user experiences a single dominant exposure peak. This pattern changes in a distributed architecture, as discussed below and quantified in Chapter 3.

Distributed Massive Multiple-Input Multiple-Output (DMMIMO) and its limit case, Cell-Free Massive Multiple-Input Multiple-Output (CF-MaMIMO), spread the antenna elements across a coverage area instead of concentrating them at a single location [6, 7, 26]. A BS is distributed when the separation between its antenna elements is much larger than the wavelength. Closely spaced elements give user channels that are less orthogonal, which limits the capacity gain [27]. Widely spaced elements give more orthogonal channels. For example, radio stripes integrate antenna panels into continuous strips along ceilings or facades. The total number of antenna elements serving a given area may be the same, but the radiation originates from multiple directions. Each access point transmits at lower power, and the probability of a strong LOS path between any single access point and a user is higher. The main communication advantage of this architecture is its cell-free nature: users are served jointly by nearby access points without handovers, which provides uniform coverage and macro-diversity [7]. A known challenge is pilot contamination, in which training sequences from different users interfere [25, 28]. The implications of distributed architectures for exposure have received less attention.

The exposure difference between collocated and distributed architectures is not obvious from the total radiated power alone. In a collocated system all beams aimed at a given user arrive from roughly the same direction, and their fields add coherently at the body surface. In a distributed system beams arrive from diverse directions around the user, and the partial decorrelation of their phases and polarizations reduces the spatial peak of the incident power density on the body. Whether the total absorbed power also decreases, or merely redistributes across the body surface, depends on the number of paths, their angular spread, and the body geometry. This angular dependence is a central question of this thesis, addressed quantitatively in Chapters 3 and 4. Both chapters find that distributed deployments reduce the peak exposure compared to collocated deployments at equal total radiated power.

Chapters 2–6 map the frequency bands and deployment architectures described above to progressively faster computational methods, from full-wave simulation through hybrid coupling to closed-form absorption laws. The detailed assignment

is given in Section 1.6.

1.4 Human exposure assessment

1.4.1 Dosimetric quantities and guidelines

The WHO commissioned twelve systematic reviews on the health effects of RF exposure [29]. In its guidance on 5G, the WHO states: “Provided that the overall exposure remains below international guidelines, no consequences for public health are anticipated” [30]. At the frequencies studied here (0.45–100 GHz), ICNIRP 2020 derives its exposure limits from the lowest adverse-effect thresholds for tissue heating, with reduction factors up to 50 for the general public [10]. Here, the oscillating electric field drives ionic conduction and molecular polarization, and the resulting energy dissipation raises the tissue temperature. Therefore, exposure guidelines limit the rate at which energy is deposited in tissue, averaged over a mass or surface area and over a six-minute time window. The six-minute interval represents the thermal time constant over which the body can redistribute or dissipate absorbed heat [10]. Sustained absorption above the guideline thresholds can produce temperature increases that exceed the thermoregulatory capacity of the tissue. The guidelines adopted in this thesis are those of the ICNIRP 2020 guidelines [10]. The IEEE C95.1 standard [31] and the U.S. Federal Communications Commission (FCC) limits [32] follow a similar structure but differ in some numerical values. All three frameworks are based on protection against established thermal effects. To study potentially overlooked biological effects, causal links in epidemiological studies need to be established, which require realistic exposure modeling and monitoring.

The SAR is the rate at which electromagnetic energy is absorbed per unit mass of tissue,

$$\text{SAR} = \frac{\sigma |\mathbf{E}|^2}{2\rho}, \quad (1.8)$$

where σ is the tissue conductivity, $\mathbf{E}$ is the internal electric field, and ρ is the tissue mass density. The whole-body averaged SAR is the total absorbed power divided by the body mass,

$$\text{SAR}_{\text{wb}} = \frac{1}{m_{\text{body}}} \int_{V_{\text{body}}} \rho(\mathbf{r}) \text{SAR}(\mathbf{r}) dV, \quad (1.9)$$

where m_{body} is the total body mass. The spatial-peak SAR is evaluated over a contiguous 10 g tissue cube and captures localized heating. The ICNIRP 2020 guidelines set the whole-body basic restriction at 0.08 W/kg for the general public and the local restriction at 2 W/kg averaged over 10 g [10]. A whole-body SAR of 4 W/kg gives a core temperature rise of about 1 °C. An additional conservative reduction factor of 10 finally sets the occupational limit to 0.4 W/kg, and a factor of 50 sets the public limit to 0.08 W/kg [10]. In addition to the local restriction, the whole-body SAR is a basic restriction at all frequencies from 100 kHz to 300 GHz.

It is not always known a priori which restriction binds first for a given exposure scenario, because the answer depends on the spatial concentration of the incident field and the body anatomy.

Above 6 GHz the penetration depth becomes small relative to the 10 g averaging volume, and the ICNIRP 2020 guidelines introduce the APD as the basic restriction [10]. The APD is defined as the net electromagnetic power absorbed per unit area of the body surface, averaged over a surface area A :

$$S_{ab} = \frac{1}{A} \int_A \frac{1}{2} \operatorname{Re}\{\mathbf{E}_t \times \mathbf{H}_t^*\} \cdot \hat{\mathbf{n}}_{in} dA, \quad (1.10)$$

where S_{ab} is the absorbed power density in W/m^2 , $\mathbf{E}_t$ and $\mathbf{H}_t$ are the transmitted electric and magnetic fields immediately inside the tissue surface, $\hat{\mathbf{n}}_{in}$ is the inward unit normal, and A is the averaging area. The ICNIRP 2020 guidelines prescribe $A = 4 \text{ cm}^2$ for the general local restriction, with an additional 1 cm^2 condition above 30 GHz. The general-public limit is 20 W/m^2 . Comparing Eq. (1.10) with Eq. (1.3) shows that S_{ab} is the fraction of the incident Poynting flux that crosses the body surface and is absorbed. The change from spatial-peak SAR to maximum APD at 6 GHz is discrete in the guidelines, although the underlying shift from volumetric to superficial absorption (Section 1.2.1) is gradual. This discontinuity is one reason that a continuous full-wave reference across the FR3 band is valuable.

The transition is based on how well spatially averaged absorption predicts local heating. Penetration depth, heat transport and tissue structure vary continuously, so the 6 GHz boundary is a practical choice within a gradual transition [10].

The ICNIRP guidelines employ a two-tier structure. Basic restrictions are limits on quantities inside the body (SAR and APD) that relate directly to the thermal effect. Reference levels are limits on external quantities, principally the incident power density S_{inc} and the incident electric field strength, that are easier to measure. A reference level is derived from the basic restriction under worst-case exposure assumptions, and compliance with the reference level is intended to guarantee compliance with the basic restriction. As the ICNIRP guidelines themselves acknowledge, in some scenarios this intended guarantee does not always hold. Several studies have shown that for certain body geometries, frequencies, and exposure conditions, the basic restriction can be exceeded even when the reference level is satisfied [11, 12]. This inconsistency arises because the reference-level derivation uses a simplified body model. Chapter 2 identifies specific frequency-and-anatomy combinations where this discrepancy occurs.

The phantoms used for dosimetric evaluation belong to the Virtual Population (ViP) family of anatomical models [33] and the Multimodal Imaging-based Detailed Anatomical model (MIDA) model. These phantoms resolve internal organ geometry at sub-millimeter resolution and assign tissue-specific dielectric properties from the Gabriel database [15]. The relevant standards are IEC/IEEE 62704 for SAR and IEC/IEEE 63195 for APD [34, 35].

Exposure assessment in practice takes two forms. In product certification a device is tested or simulated under standardized worst-case conditions to verify

compliance with the basic restriction. In network assessment the incident field from one or more BSs is measured or simulated in a representative environment and compared to the reference level. Both approaches require either full-wave simulation on an anatomical phantom or calibrated measurement equipment. Full-wave simulation gives the complete internal field distribution and can evaluate both SAR and APD directly. Measurement gives the external field and can verify reference-level compliance, but converting measured fields to absorbed power requires additional modeling. The gap between what is measured and what is regulated motivates the computational methods developed in this thesis, which connect environmental fields to dosimetric quantities without the cost of full-wave simulation at every evaluation point.

1.4.2 Worst-case assessment

Worst-case exposure assessment quantifies the maximum absorption that a standard-compliant field can produce in the human body. Dimbylow computed whole-body averaged and spatial-peak SAR in the NORMAN adult phantom from 10 MHz to 3 GHz using FDTD [36]. Uusitupa *et al.* extended this work to fifteen different voxel models and showed that body-mass index and height are the primary determinants of inter-individual SAR variation between 300 MHz and 5 GHz [37]. Bakker *et al.* compared child and adult phantoms and found that children can exceed adult SAR levels by up to 45% at certain frequencies when exposed to the same incident field [38]. These studies established the reference values that underpin the current guideline limits. The worst-case methodology is mature and well understood for frequencies below 6 GHz.

Above 6 GHz, worst-case assessment is less studied. Early studies used simplified body geometries, representing the head as a sphere or the torso as a multilayered slab, to compute the APD under plane-wave exposure [39, 40]. These models capture the depth-dependent absorption and the effect of tissue layering but cannot represent anatomical features such as the ear canal, the nose, or the curvature of the limbs. Kodera *et al.* computed whole-body SAR on adult phantoms up to 100 GHz [41], but child phantoms were not included. The available data for children above 6 GHz remain sparse. Chapter 2 contains 550 FDTD simulations across adult and child phantoms from 450 MHz to 26 GHz, with phantom coverage varying by frequency. To the best of our knowledge, this is the first systematic child–adult far-field APD comparison across the 7–15 GHz FR3 band.

Worst-case assessment is conservative by construction. It answers the question of whether a device or network can, under any circumstance, produce absorption above the basic restriction. It does not answer the question of how much absorption a person actually receives in a given environment, under a given network load, over a given period. The gap between the worst case and the realistic case can span several orders of magnitude. A BS that complies with the reference level at its maximum power and nearest approach distance produces far less exposure in practice, because the beam is shared among multiple users, the traffic load varies, and the person is rarely at the closest point. Bridging this gap requires methods that

model both the propagation environment and the body under realistic conditions.

1.4.3 Realistic assessment

Several groups have approached the problem of realistic exposure assessment. Vermeeren *et al.* combined statistical descriptions of the indoor multipath channel with whole-body SAR data to estimate the distribution of exposure in rooms with reflective boundaries [42]. Bamba *et al.* measured the absorption cross-section of human subjects in a reverberation chamber and related it to whole-body SAR under diffuse-field conditions [43]. Network-level measurement campaigns have measured the spatial distribution of the incident field from a deployment of BSs [8], but these studies typically stop at the field level and do not compute the absorption in a human body. The common limitation is that the propagation environment and the human body are addressed separately, with the link between the two handled by simplified assumptions.

Fast exposure methods also include WLAN surrogate models [44], low-rank stochastic dosimetry [45], base-station SAR estimation formulas [46], and integrative near- and far-field assessment [47]. Indoor ray tracing (RT) predictions of spatial channel correlation at 2.61 GHz have also been compared with a robotic 64-antenna MaMIMO testbed, with an error of at most 10% [48].

The hybrid simulation approach couples a propagation solver to a full-wave body solver. Shikhantsov *et al.* introduced a RT/FDTD coupling in which FDTD step-responses for a discrete set of directions of arrival are precomputed and then combined along the ray-traced multipath directions to evaluate the absorbed power [20, 49]. This approach retains the site-specific accuracy of RT and the dosimetric completeness of FDTD, but each direction requires a full FDTD simulation. At mmWave frequencies, where the FDTD cell size shrinks to a fraction of a millimeter, the cost of a single body simulation becomes substantial. The hybrid method was applied at 3.5 GHz in an indoor environment and provided the first site-specific dosimetric results for MaMIMO. Extension to mmWave frequencies and realistic outdoor environments had not been reported.

Several groups have reduced whole-body absorption above 6 GHz to one fitted coefficient times a body area. Bamba *et al.* derived an absorption efficiency of about 0.5 for diffuse fields between 1.5 and 6 GHz [50]. Flintoft *et al.* and Zhang *et al.* measured the absorption cross-section of volunteers in a reverberation chamber and found it proportional to body surface area above 6 GHz [51, 52]. Kodera *et al.* showed with full-wave simulations from 1 to 100 GHz that the whole-body SAR equals a transmission coefficient times the projected area of the body [41]. Diao *et al.* found the same up to 30 GHz [53]. The coefficient falls between 0.4 and 0.7 in every study, but it is fitted separately per phantom and per frequency, and no study writes it as one expression or treats a nonconvex body. Chapter 5 derives the closed form behind these coefficients.

Despite these advances, no end-to-end method connected a realistic wireless deployment to the absorbed dose in a human body across the full range of current and emerging frequencies. Systematic APD data for children at mmWave and

FR3 frequencies were unavailable. The hybrid RT/FDTD approach had not been extended to mmWave, where the computational cost of the body simulation is highest. No city-scale framework could evaluate exposure under realistic deployment conditions in a reasonable time, because every evaluation point required a separate FDTD run. There was no closed-form model accurate enough to replace the full-wave body computation while retaining compatibility with ray-traced or stochastic channel data. These gaps define the scope of this thesis. Each subsequent chapter addresses one gap in the chain from deployment to absorbed dose.

1.5 Computational methods

1.5.1 Finite-difference time-domain method

The FDTD method advances the electric and magnetic fields in time on a staggered Cartesian Yee grid [54]. The method is suited to parallel computation on GPUs. The method handles arbitrary material distributions, including the heterogeneous tissue properties of an anatomical phantom, without any simplifying assumptions about the body geometry. It naturally captures near-field coupling, standing waves inside the body, and all polarization effects. For these reasons FDTD is the standard method for computational dosimetry. Validation studies report a relative error of about 5% for FDTD SAR calculations [55, 56]. The commercial solver Sim4Life implements this method on GPU hardware and is used for the dosimetric computations in Chapters 2, 3, and 4.

The computational cost of FDTD scales with the number of cells in the simulation volume and the number of time steps required for convergence. A spatial resolution of ten cells per wavelength is a common minimum for adequate sampling of the field. At 3.5 GHz this gives a cell size of approximately 0.9 mm. At 28 GHz the cell size drops to approximately 0.1 mm. For a fixed physical volume, the number of cells grows as f^3 . The Courant stability condition [57] ties the time step to the cell size, adding a further factor of f , so the total computational work grows approximately as f^4 . A whole-body simulation at 26 GHz requires on the order of 10^{10} cells and runs for hours on a multi-GPU system [13]. If the simulation must also include the surrounding environment at a scale of tens of meters, the cell count reaches 10^{12} and exceeds the memory of current hardware.

The consequence of this cost scaling is that FDTD is a body-scale method. It resolves the internal field distribution in a phantom with full anatomical detail, but it cannot simultaneously model the propagation environment at the scale of a wireless deployment. A separate method must provide the incident field at the body boundary. The hybrid approaches in Chapters 3 and 4 make this separation explicit: a propagation solver computes the multipath field in the environment, and FDTD computes the resulting absorption in the body. In Chapter 2, FDTD is used in its natural role of evaluating the absorbed power produced by a known plane-wave incident field. The 550 simulations in that chapter each run in isolation, without modeling the environment that produced the incident field.

1.5.2 Ray tracing

RT computes electromagnetic propagation by launching rays from a source into a three-dimensional model of the environment and tracing their interactions with surfaces. Each ray undergoes specular reflection, transmission, and diffraction according to the laws of geometrical optics and the uniform theory of diffraction. The method is a high-frequency asymptotic technique that becomes more accurate as the wavelength decreases relative to the environmental features. A site-specific RT simulation requires a three-dimensional geometric model of the environment with associated material properties. The output is a set of propagation paths, each characterized by its amplitude and phase, delay, and departure and arrival angles. These paths form the CIR of Eq. (1.7). Two RT implementations are used in this thesis: the commercial solver Wireless InSite in Chapters 3 and 4, and the differentiable ray tracer Sionna in Chapters 5 and 6.

The strength of RT is its ability to model propagation at the scale of entire buildings, streets, and city blocks with site-specific accuracy. Unlike stochastic models, RT captures the spatial structure of the multipath field at each location in the environment. This makes it suitable for exposure assessment, where the field varies on a wavelength scale around the body. The limitations are threefold. First, RT requires a geometrically accurate three-dimensional model, which may not be available or may lack the material properties needed at mmWave frequencies. Second, the cost grows with the number of surfaces and the maximum number of interactions per ray, making large outdoor deployments computationally intensive. Third, and most relevant for this thesis, RT treats the body as a receiving point or simplified blocker and outputs incident paths; it does not compute the internal field. It provides no dosimetric information on its own.

Therefore, RT is an environment-scale method. It reaches the spatial scales that FDTD cannot, but it lacks the material-resolving capability that dosimetry requires. The complementarity between RT and FDTD is the basis for the hybrid approach pursued in this thesis. RT provides the multipath field at the body surface, and FDTD computes the absorption from that field. The Huygens surface described in Section 1.2.3 serves as the interface between the two methods. In Chapter 5 the FDTD step is replaced by a closed-form absorption law that takes the same ray-traced paths as input, removing the body simulation entirely and enabling the evaluation of thousands of body positions in the time previously needed for one.

1.5.3 Geometry-based stochastic models

A geometry-based stochastic channel model (GSCM) generates statistically representative channel realizations without requiring a site-specific three-dimensional model. The approach defines scatterers at geometrically plausible positions around the transmitter and receiver and assigns statistical distributions to the large-scale parameters such as path loss, delay spread, and angular spread. The 3rd Generation Partnership Project (3GPP) Technical Report 38.901 [58] standardizes this approach with calibrated parameter sets for standard deployment scenarios. The quasi-

deterministic radio channel generator (QuaDRiGa) implements the 3GPP 38.901 model and earlier GSCMs [59] and provides spatially consistent channel realizations along a user trajectory, which is needed for time-continuous exposure evaluation. The output is a CIR with the same structure as the ray-traced output. A GSCM is fast, reproducible, and standardized, making it suitable for statistical studies that require many channel realizations under controlled conditions.

The limitation of a GSCM is that it does not model a specific site. The generated channels are statistically correct for a given scenario class, such as urban macrocellular or indoor office, but they do not reflect the geometry of a particular building or street. The fields produced by a GSCM cannot be tied to a location on a real map. For exposure assessment this means that a GSCM alone cannot answer the site-specific question of what absorption a person receives at a given position. It can answer the statistical question of what absorption a person receives on average across many positions drawn from a given scenario. Chapter 4 combines QuaDRiGa with site-specific RT to obtain both statistical consistency and spatial specificity.

1.5.4 Hybridization

No single computational method spans the range of spatial scales between the wireless environment and the absorbing body tissue accurately, efficiently, and at all RF frequencies. FDTD resolves the body with full anatomical detail but cannot model the environment. RT models the environment with site-specific accuracy but does not compute internal fields. A GSCM provides statistical channels cheaply but without site specificity. This thesis hybridizes these methods. The propagation environment is modeled by RT, by QuaDRiGa, or by a combination of the two. The incident field reaches the body through one of two interfaces (Fig. 1.6): a list of far-field paths that arrive as plane waves on the body surface, or a Huygens surface on which the tangential fields are recorded and re-radiated inward. FDTD resolves the absorption inside the body. Where the cost of repeated FDTD body simulations becomes prohibitive, the full-wave step is replaced by a closed-form surface-absorption law that takes the same incident paths or Huygens-box fields as input. The quantity preserved across every handover is the angular electromagnetic field, not a received-power scalar. This choice keeps the incidence direction, polarization, and phase information that absorption depends on, regardless of which computational method produced it.

The resulting computational framework is organized as a methods *ladder*. At the top, the full-wave FDTD method of Chapter 2 provides the most detailed and expensive dosimetric computation. The hybrid methods of Chapters 3 and 4 couple propagation to the body through a Huygens surface, with full-wave accuracy for the body at the cost of one FDTD simulation per incident-field configuration. The closed-form laws of Chapter 5 eliminate the FDTD step entirely and express the absorbed power as a function of the incident field directions and the body geometry, evaluated in milliseconds. Chapter 6 compares the simulated fields with measurements in controlled and realistic environments. Each step trades generality

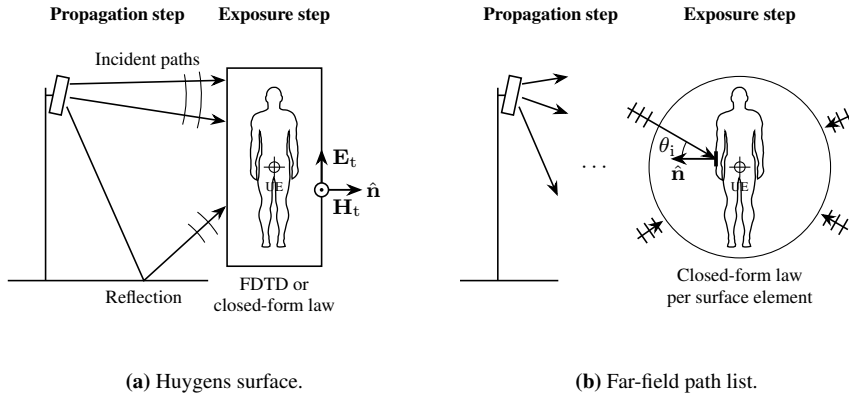


Figure 1.6: The two interfaces between the propagation step and the exposure step, with the user equipment (UE) near the body. (a) A Huygens surface: the tangential fields $\mathbf{E}_t$ and $\mathbf{H}_t$ on a closed surface, with outward normal $\hat{\mathbf{n}}$ ($\odot$: out of the page), are re-radiated inward, to FDTD (Chapters 3, 4, and 6, anechoic room) or, as the incident field at the body surface, to the closed-form law of Chapter 5 (Chapter 6, indoor room). (b) A far-field path list: each path arrives as a plane wave on the body from direction (θ, φ) , and the closed-form law evaluates the absorption per surface element with local normal $\hat{\mathbf{n}}$ and incidence angle θ_i (Chapters 5 and 6, city scale).

for computational reach. Each method is validated against the one above it.

1.6 Problem statement, contributions, and outline

Realistic, guideline-relevant exposure assessment of next-generation wireless networks requires calculations of both propagation and absorption in the body. The spatial scales span five orders of magnitude, so repeated anatomical full-wave calculations are computationally costly. Full-wave simulation of the combined environment and body is infeasible at mmWave frequencies. Hybrid methods that couple propagation and dosimetry have been shown only at sub-6 GHz frequencies and in controlled indoor settings. No closed-form dosimetric model was accurate enough to replace the full-wave body computation while remaining compatible with channel data from ray tracers or stochastic models.

The thesis has four research questions. The relevant chapters are listed below each question. Chapter 7 presents summaries of the answers.

- RQ1.** What is the full-wave dosimetric baseline across age, frequency, and exposure scenario, and which basic restriction (whole-body SAR, local SAR, or APD) binds first? *Answered in Chapter 2.*

- RQ2.** How can site-specific propagation be coupled to full-wave dosimetry at mmWave frequencies, and what does the coupling reveal about distributed versus collocated MaMIMO architectures? *Answered in Chapters 3 and 4.*
- RQ3.** Can the absorbed power be expressed in closed form, for both incoherent and coherent multipath, accurately enough to replace full-wave dosimetry and fast enough to enter the beamformer design loop and reach city scale? *Answered in Chapter 5.*
- RQ4.** Do the simulated fields agree with measurements in controlled and in realistic environments? *Answered in Chapter 6.*

Fig. 1.7 shows the thesis structure as a methods ladder. The contributions and content of each chapter are summarized below; publication tags refer to the list in Section 1.7.

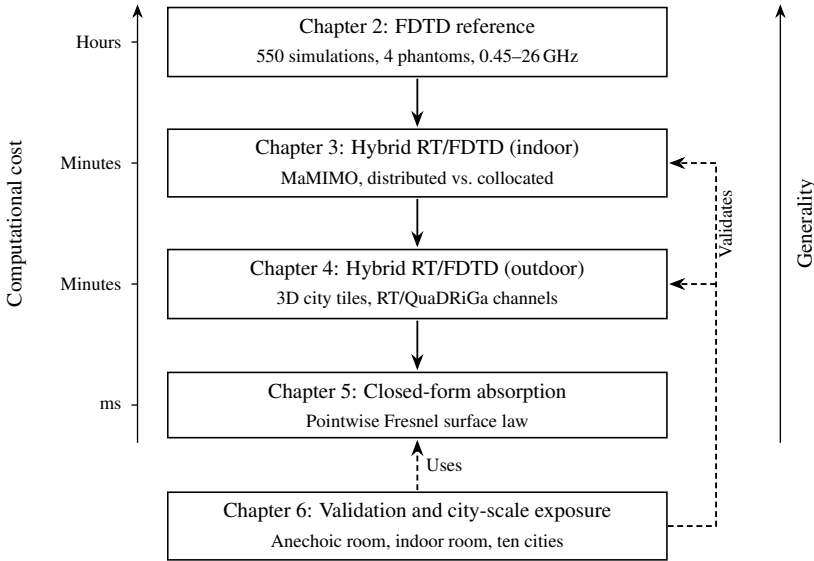


Figure 1.7: Thesis structure as a methods ladder. Each chapter develops a computational method that is faster but less general than the one above (solid arrows). Chapter 6 validates the hybrid methods of Chapters 3 and 4 against measurements and uses the closed-form law of Chapter 5 (dashed arrows).

Chapter 2 establishes the full-wave dosimetric reference [A1.2]. It presents 550 FDTD simulations across four ViP phantoms (two adults, two children) from 450 MHz to 26 GHz, covering environmental and auto-induced exposure under plane-wave and focused-beam incidence. The chapter quantifies the frequency and age dependence of whole-body SAR and localized APD. To the best of our knowledge, this is the first systematic child–adult far-field APD comparison across

the 7–15 GHz FR3 band. The chapter also shows specific conditions under which reference-level compliance does not ensure basic-restriction compliance.

Chapter 3 couples site-specific ray-traced propagation to full-wave dosimetry through a Huygens surface [A1.1]. The chapter extends the hybrid RT/FDTD method to mmWave frequencies and applies it to a realistic indoor environment at 3.5 and 28 GHz, comparing the exposure produced by a collocated MaMIMO BS with that of a distributed deployment at equal total radiated power. The distributed architecture produces substantially lower peak APD than the collocated architecture.

Chapter 4 extends the hybrid framework to large outdoor environments using photorealistic three-dimensional city models [A2.1]. A pipeline extracts RT parameters from Google Earth tiles, generates spatially consistent QuaDRiGa channels, and evaluates the absorbed power via FDTD. The chapter compares collocated and CF-MaMIMO deployments in two city environments and cross-validates the stochastic channels against deterministic RT results.

Chapter 5 replaces the full-wave body computation with closed-form absorption laws derived from Fresnel theory and integral geometry [A1.3, A1.4]. The incoherent law reduces whole-body absorbed power to a single flux-weighted Fresnel transmission scalar. The coherent extension assembles a closed-form exposure operator from ray-traced paths, enabling absorbed-power maps in milliseconds and exposure-constrained beamforming without FDTD. The chapter validates both formulations against Mie theory, full Fresnel calculations, and FDTD data. A European patent application for the core method has been filed [P.1].

Chapter 6 validates the propagation and exposure models against measurements and applies them at city scale [C1.3, C1.6, A1.5, A1.6]. In a controlled anechoic environment at 26 GHz, the hybridization procedure reproduces a beamformed hot-spot. In a realistic indoor room at 28 GHz, a digital twin calibrated from phaseless robotic scans predicts the spatial interference pattern. A Huygens box around the phantom couples the twin's field to the closed-form surface law of Chapter 5, and the computed exposure is well below the general-public APD basic restriction. The chapter then applies the methods to compute route-level whole-body exposure across ten cities at 15 GHz.

Chapter 7 presents the overall conclusions of this thesis and future research directions. Moreover, it compares the computational cost, accuracy, and applicability of the methods developed in the preceding chapters and answers the four research questions.

This research was conducted at the WAVES research group, Department of Information Technology, Ghent University and imec, Belgium. A research stay at the IT'IS Foundation and Zurich MedTech AG was funded by the Research Foundation Flanders (FWO, file number K215823N). Chapter 2 was carried out within the GOLIAT project (5G expOsure, causaL effects, and rIsk perception through citizen engAgement) under the European Union Horizon Europe programme [60]. Chapters 3 and 4 were supported in part by the European Research Council (ERC) through ATTO: A New Concept for Ultra-high Capacity Wireless Networks under Grant 695495 and in part by Methusalem through SHAPE: Next Generation Wireless Networks. Chapter 6 was carried out within the same projects, in collaboration

with IDLab at INTEC, Ghent University and imec.

Contributions to the research

The publications and manuscripts underlying Chapters 2–6 have several co-authors, with me as first author throughout. I carried out the technical work, wrote the first complete drafts, developed the research software and produced the figures. For Chapter 3, I adapted and modified Sergei Shikhantsov’s hybrid ray-tracing/FDTD implementation. Olivier Caytan helped carry out the Chapter 6 experiment, particularly the transmitter and the anechoic room.

I discussed the work each month with Wout Joseph, Emmeric Tanghe, Günter Vermeeren and Sergei Shikhantsov in the WAVES team. Their feedback concerned technical questions, the research direction and the selection of results to report. Every two months, I also discussed the GOLIAT studies with Bram Stroobandt, Silvia Gallucci, Marta Parazzini, Gabriella Tognola, Joe Wiart, Mònica Guxens and Wout Joseph. Some research questions followed the GOLIAT project outline. Senior researchers developed that outline and secured its funding. Olivier Caytan, Hendrik Rogier and Sam Lemey gave feedback on relevant publications and helped acquire funding through ATTO and SHAPE.

1.7 Publications

The following publications and manuscripts were produced during this doctoral research. Chapters 2, 3 and 4 are based on peer-reviewed journal articles. The manuscripts underlying Chapters 5 and 6 have been submitted for journal publication. The list also includes conference publications and other co-authored work.

A1 journal publications (first author)

- [A1.1] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, P. Demeester, and W. Joseph, “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.
- [A1.2] **R. Wydaeghe**, B. Stroobandt, S. Gallucci, M. Parazzini, G. Tognola, J. Wiart, G. Vermeeren, M. Guxens, E. Tanghe, and W. Joseph, “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, Sept. 2, 2026, doi: 10.1088/1361-6560/ae97ac.
- [A1.3] **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.*

- [A1.4] **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.*
- [A1.5] **R. Wydaeghe**, G. Vermeeren, E. Tanghe, and W. Joseph, “Human-centric 6G RF-EMF exposure with AI-assisted digital twins in ten cities,” manuscript submitted to *IEEE Open J. Commun. Soc.*
- [A1.6] **R. Wydaeghe**, O. Caytan, G. Vermeeren, H. Rogier, S. Lemey, E. Tanghe, and W. Joseph, “Digital twin calibrated from phaseless 28 GHz measurement scans for indoor exposure assessment,” manuscript submitted to *IEEE Antennas Wireless Propag. Lett.*
- [A1.7] **R. Wydaeghe**, B. Stroobandt, G. Vermeeren, E. Tanghe, M. Guxens, and W. Joseph, “GOLIAT: a configurable workflow for near- and far-field RF-EMF dosimetry in Sim4Life,” manuscript submitted to *SoftwareX*, 2026. Preprint doi: 10.2139/ssrn.7590236.

A2 journal publications (first author)

- [A2.1] **R. Wydaeghe**, S. Shikhantsov, G. Vermeeren, L. Martens, E. Tanghe, and W. Joseph, “Hybrid ray-tracing–QuaDRiGa/FDTD method for realistic 28 GHz exposure with 6G CF-MaMIMO in 3D outdoor environments,” *npj Wireless Technology*, vol. 2, no. 1, Art. no. 13, Apr. 2026, doi: 10.1038/s44459-026-00031-4.

A1 journal publications (co-author)

- [A1.8] M. Leeman, **R. Wydaeghe**, J. Van der Straeten, S. Goegebeur, G. Vermeeren, and W. Joseph, “City-scale spatio-temporal modeling of 5G downlink exposure of users and non-users by ray-tracing in a real urban environment,” *IEEE Access*, vol. 13, pp. 30894–30906, 2025, doi: 10.1109/ACCESS.2025.3541352.
- [A1.9] M. Stamets, G. Castaño-Vinyals, P. De Llobet Viladoms, A. Veludo, A. Thielens, L. Martin, **R. Wydaeghe**, S. Aerts, M. Parazzini, G. Tognola, J. Wiart, K. Polanska, M. Popovic, M.-J. López, M. Maule, W. Joseph, J. Grellier, M. Rösli, and M. Guxens, “Characterizing digital communication device use among young people from 4 European countries: cross-sectional survey study,” *J. Med. Internet Res.*, vol. 27, e76767, Dec. 2025.
- [A1.10] H. Jalilian, L. Belácková, G. Costa, S. Dongus, J. Fröhlich, M. Guxens, H. Herssens, A. Huss, W. Joseph, N. Loizeau, M. Parazzini, N. Sandoval Diez, B. Stroobandt, A. Thielens, G. Tognola, A. Fernandes Veludo, V. Jaki Waibl, J. Wiart, I. Wipf, **R. Wydaeghe**, M. Zahner, and M. Rösli, “Development of a model to estimate cumulative radiofrequency electromagnetic field exposure,” manuscript submitted to *Environmental Research*, 2026.

C1 conference publications (first author)

- [C1.1] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, P. Demeester, and W. Joseph, “Realistic human exposure from a 28 GHz and 3.5 GHz base station using a hybrid ray-tracer/FDTD method,” in *BioEM 2022*, Nagoya, Japan, June 2022, p. 123.
- [C1.2] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, P. Demeester, and W. Joseph, “New hybrid QuaDRiGa-FDTD method for realistic human exposure assessment at 28 GHz with 6G cell-free massive MIMO in 3D outdoor environments,” in *BioEM 2023*, Oxford, U.K., June 2023, pp. 30:03–06.
- [C1.3] **R. Wydaeghe**, A. Moerman, O. Caytan, S. Shikhantsov, E. Tanghe, G. Vermeeren, H. Rogier, S. Lemey, P. Demeester, and W. Joseph, “New hybrid ray-tracing/FDTD for EMF exposure in 6G networks using semantically classified Google Earth photogrammetry with measurement validation,” in *Proc. 18th European Conference on Antennas and Propagation (EuCAP)*, Glasgow, U.K., March 2024, pp. 18:2–5.
- [C1.4] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, P. Demeester, and W. Joseph, “Accelerating mmWave exposure simulations and the OUTREACH idea to industry,” in *BioEM 2024*, Crete, Greece, June 2024.
- [C1.5] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, and W. Joseph, “Characterization of EMF hotspots for realistic exposure assessment in end-to-end simulations using a hybrid QuaDRiGa/FDTD tool,” in *BioEM 2024*, Crete, Greece, June 2024.
- [C1.6] **R. Wydaeghe**, O. Caytan, S. Shikhantsov, E. Tanghe, G. Vermeeren, H. Rogier, S. Lemey, P. Demeester, and W. Joseph, “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. European Conference on Antennas and Propagation (EuCAP)*, Stockholm, Sweden, March 2025, pp. 19:1–5.
- [C1.7] **R. Wydaeghe**, B. Stroobandt, M. Guxens, J. Wiart, G. Tognola, M. Parazzini, and W. Joseph, “Far-field environmental and auto-induced RF-EMF human absorption simulations in different phantoms,” in *BioEM 2025*, Rennes, France, June 2025.

C1 conference publications (co-author)

- [C1.8] M. Leeman, **R. Wydaeghe**, J. Van der Straeten, G. Vermeeren, and W. Joseph, “Spatio-temporal modelling of urban 5G downlink exposure of users and non-users by ray-tracing,” in *BioEM 2025*, Rennes, France, June 2025.

- [C1.9] S. Gallucci, **R. Wydaeghe**, A. Conforti, B. Stroobandt, M. Benini, G. Tognola, J. Wiart, M. Parazzini, and W. Joseph, “Numerical assessment of human near-field exposure in the EU GOLIA project: a multi-frequency analysis across different anatomical models,” in *BioEM 2025*, Rennes, France, June 2025.
- [C1.10] H. Jalilian, A. Veludo, B. Stroobandt, **R. Wydaeghe**, I. Wipf, G. Castaño-Vinyals, G. Tognola, M. Parazzini, J. Wiart, M. Guxens, W. Joseph, and M. Röösli, “A novel approach to estimate radio frequency electromagnetic dose in everyday life for epidemiological research and risk communication,” in *BioEM 2025*, Rennes, France, June 2025.

C3 conference contributions (first author)

- [C3.1] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, P. Demeester, and W. Joseph, “New hybrid QuaDRiGa-FDTD method for realistic human exposure assessment at 28 GHz with 6G cell-free massive MIMO in 3D outdoor environments,” COST Action CA20120 (INTERACT), Technical Document TD(23)06026, Poznan, Poland, Sep. 12–14, 2023.
- [C3.2] **R. Wydaeghe**, S. Shikhantsov, E. Tanghe, G. Vermeeren, L. Martens, and W. Joseph, “Hybrid ray-tracing–QuaDRiGa/FDTD method for realistic human exposure assessment at 28 GHz with 6G CF-MaMIMO in 3D outdoor environments,” COST Action CA20120 (INTERACT), Technical Document TD(25)10062, Dublin, Ireland, Jan. 27–30, 2025.

Patents

- [P.1] **R. Wydaeghe** and W. Joseph, “Determining electromagnetic absorption in a body,” European patent application EP 26214213.6, Ghent University, filed Oct. 26, 2026.

Software and datasets

- [V.1] **R. Wydaeghe**, *GOLIA: Comprehensive Automated Near- and Far-Field SAR Assessments Using Sim4Life*, ver. 1.4.0, Python software, Jan. 15, 2026. [Online]. Available: <https://github.com/rwydaegh/goliat>.
- [V.2] **R. Wydaeghe**, B. Stroobandt, S. Gallucci, M. Parazzini, G. Tognola, J. Wiart, G. Vermeeren, M. Guxens, E. Tanghe, and W. Joseph, “Dataset for: Environmental and auto-induced RF-EMF adult and children far-field exposure simulations between 450 MHz and 26 GHz,” Harvard Dataverse, 2026, doi: 10.7910/DVN/EEEE0X.

Awards

- [AW.1] Second winner of the Student Poster Award, BioEM 2022, Nagoya, Japan, June 2022.
- [AW.2] Second winner of the Student Platform Award, BioEM 2024, Crete, Greece, June 2024.
- [AW.3] Third winner of the Sim4Life Student Competition 2025, announced Jan. 20, 2026.

Scientific reviewing

The author has reviewed manuscripts for *IEEE Transactions on Antennas and Propagation*, *IEEE Open Journal of Vehicular Technology*, and *npj Wireless Technology*.

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2

Full-Wave Dosimetry Across Radio Frequencies

“We don’t want any adventures here, thank you!”

— Bilbo Baggins, *The Hobbit*

This chapter is adapted from:

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In Chapter 1, we introduced the difference in spatial scale between wireless propagation and absorption in tissue. In this chapter, we establish the full-wave dosimetric reference for the methods developed further in the thesis. We use finite-difference time-domain simulations to quantify environmental and auto-induced radio-frequency electromagnetic-field exposure in four anatomically realistic adult and child phantoms from 450 MHz to 26 GHz.

The simulations show how frequency, anatomy, incidence direction, polarization, and coherent focusing affect whole-body and localized absorption. Each incident field requires a separate full-wave calculation, and the computational cost increases with frequency.

2.1 Introduction

5G and prospective 6G networks span three frequency ranges: FR1 (450 MHz–6 GHz), FR2 (24–52.6 GHz for 5G mmWave), and the prospective FR3 (7–15 GHz for 6G) [1, 2]. When a MaMIMO base station beamforms toward an active user, the resulting exposure is *auto-induced* because the user’s position determines the beam [3]. For non-users or 4G users without beamforming, exposure is *environmental*. Auto-induced exposure concentrates energy toward the user, whereas environmental exposure can involve fields incident from many directions. Adult and child phantoms are both needed because anatomy and tissue dielectric properties change with age [4].

Computational dosimetry quantifies SAR and APD induced in human tissues by external electromagnetic fields [5, 6]. Previous far-field studies characterized whole-body and localized SAR from plane-wave exposure using anatomically realistic phantoms. Dimbylow [7] established baseline SAR values for an adult model (NORMAN) from 10 MHz to 3 GHz, including scaled child versions. Uusitupa *et al.* [8] extended this to 15 voxel models (18–105 kg) from 300 MHz to 5 GHz. Whole-body SAR at the ICNIRP reference level approached basic restrictions for small children. Posture, polarization, and incidence direction significantly affected results. Bakker *et al.* [9] compared induced SAR in child and adult models from 10 MHz to 5.6 GHz, finding that whole-body SAR exceeded the basic restriction by up to 45% in small children at the reference level. Kühn *et al.* [10] and Vermeeren *et al.* [11] showed that reference levels derived from simplified models are not always consistent with basic restrictions when evaluated on detailed anatomical phantoms or realistic multipath environments. Vermeeren *et al.* [12] applied a stochastic method for assessing whole-body SAR in realistic multipath environments by combining single plane-wave FDTD simulations.

These studies focused on sub-6 GHz frequencies and isotropic (environmental) exposure from uniformly distributed plane waves. The ICNIRP 2020 guidelines [13] introduced APD as the basic restriction above 6 GHz, replacing volumetric SAR, with a surface metric averaged over 4 cm^2 . Hirata *et al.* [14] reviewed computational dosimetry studies supporting this transition, confirming that APD correlates with tissue temperature rise at millimeter-wave frequencies. Recent APD studies above 6 GHz used simplified models, including planar slabs [15], spherical heads [16], and isolated ear structures [17], typically at single frequencies and without cross-phantom comparisons.

Morelli *et al.* [18] compared child and adult anatomical models exposed to a nearby 28 GHz device, with the mesh limited to the exposed body region. Here, we compare far-field environmental and focused exposure across the 7–15 GHz band. Whole-body average SAR has been computed up to 100 GHz in adult models [19], but child phantoms have not been included. No study has evaluated far-field APD in realistic whole-body phantoms across the 6G upper mid-band (7–15 GHz). Previous MaMIMO work coupled ray-tracing with FDTD for specific indoor [20, 21] and outdoor [22] environments, but these scenario-specific studies do not yield exposure estimates directly comparable across phantoms, frequencies, and technologies.

Three gaps limit current understanding of far-field radio frequency (RF)–electromagnetic field (EMF) exposure in the 5G/6G era: (1) No single study spans the full spectral range from sub-GHz cellular bands through the 6G upper mid-band and into millimeter wave (26 GHz) while including child phantoms, capturing how dosimetric metrics evolve as penetration depth decreases from tens of millimeters to one millimeter. (2) Child exposure remains under-characterized at higher frequencies. Existing studies typically include one or two child models, making inter-individual variability difficult to assess. (3) Auto-induced exposure, where beamforming creates localized hot-spots near the body, has not been systematically evaluated against ICNIRP 2020 basic restrictions across phantoms and frequencies.

This chapter addresses these gaps with FDTD simulations covering 15 frequencies (450 MHz–26 GHz), four ViP phantoms [23] (two adults, two children), and two exposure scenarios: environmental and auto-induced exposure. Environmental exposure uses plane-wave illumination from six orthogonal directions with two polarizations each, as in Bakker *et al.* [9] and Uusitupa *et al.* [8]. Auto-induced exposure uses four-direction beamforming toward a hypothetical UE location. We compute $\text{psSAR}_{10\text{g}}$, whole-body SAR, and organ-specific SAR following the IEC/IEEE 62704-1 standard [24] below 6 GHz, and APD following the IEC/IEEE 63195-2 standard [25] at or above 6 GHz. To the best of our knowledge, this is the first child–adult far-field APD comparison across the 7–15 GHz band. We also calculate whole-body SAR at 26 GHz for Thelonious. The 550 simulations enable comparisons between phantoms and frequency bands revealing how compliance margins with ICNIRP 2020 basic restrictions vary with body size, frequency, and exposure scenario. At 3500 MHz, auto-induced beamforming meets the ICNIRP reference level yet exceeds the local-SAR basic restriction. At 7 GHz, APD is near the basic restriction. Below 6 GHz the compliance metric is whole-body SAR. Above it, the metric is APD.

The results inform regulators by identifying frequency–phantom combinations where compliance margins narrow (e.g., 7 GHz auto-induced exposure in child phantoms). The ICNIRP guidelines set no organ-specific basic restriction. Epidemiological studies use organ-level dose to relate exposure to long-term biological outcomes from surveyed usage patterns [26–28]. Such dose modeling requires organ-specific SAR across many frequencies, phantoms, and exposure scenarios. We provide an open dataset of the compliance metrics and the organ-specific SAR, for adults and children, from 450 MHz to 26 GHz [29].

2.2 Methods

Tables 2.1 and 2.2 list the complete simulation configuration used throughout this section.

Table 2.1: FDTD simulation parameters and computational requirements in FR1.

<i>Frequency bands and exposure scenarios</i>					
Frequency [MHz]	Technology	Environmental	Auto-induced		
450	LTE	✓	–		
700	5G NR	✓	✓		
835	GSM-850	✓	–		
1450	LTE	✓	–		
2140	LTE	✓	–		
2450	Wi-Fi	✓	–		
3500	5G NR	✓	✓		
5200	Wi-Fi	✓	–		
5800	Wi-Fi	✓	–		
<i>Basic quantities: psSAR_{10g}, SAR_{wb}, SAR_{osa}, and SAR_{group} (brain, skin, eyes, and genitals), normalized to 1 W/m² according to IEC/IEEE 62704-1. APD was not evaluated in FR1.</i>					
<i>Spatial and temporal resolution</i>					
Frequency	Cell size Δx [mm]	Time step Δt [ps]	Skin mesh holes [%]	Cells per δ_{90}	Cells per 10 g side
450	2.5	4.81	13.1	24	9
700	2.5	4.81	13.1	21	9
835	2.5	4.81	13.1	19	9
1450	2.5	4.81	13.1	15	9
2140	1.694	3.26	1.0	17	13
2450	1.482	2.85	0	18	15
3500	1.0	1.93	0	19	22
5200	1.0	1.93	0	11	22
5800	1.0	1.93	0	10	22
<i>Absorption depth and spatial resolution in tissue</i>					
Frequency	δ_{90} eye [mm]	δ_{90} muscle [mm]	Cells/ λ eye	Cells/ λ muscle	Cells/ λ skin
450	36	59	32	35	39
700	33	53	21	23	26
835	32	50	17	19	22
1450	28	39	10	11	13
2140	23	29	10	11	13
2450	21	26	10	11	13
3500	15	17	10	12	14
5200	8.8	10	7	8	10
5800	7.5	8.7	6	7	9
<i>Computational domain size [million cells]</i>					
Frequency	h	Duke	Ella	Eartha	Thelonious
450	1	28	23	16	11
700	1	28	23	16	11
835	1	28	23	16	11
1450	1	28	23	16	11
2140	1	83	70	47	32
2450	1	121	103	69	46
3500	1	376	318	210	142
5200	1	376	318	210	142
5800	1	376	318	210	142

Environmental exposure uses individual plane waves from the stated incidence directions and polarizations. Auto-induced exposure uses equal-gain, phase-only focusing at the user-equipment location. The time step satisfies the Courant limit. At FR1 frequencies, the 90% absorption depth extends beyond the skin layer and is therefore not reported for skin. The 10 g cube side is 21.5 mm. The relative-permittivity ranges for eye, muscle, and skin are 69–31, 57–26, and 46–18. Full-domain dimensions are $54 \times 28 \times 181$ cm for Duke, $50 \times 28 \times 163$ cm for Ella, $45 \times 23 \times 139$ cm for Eartha, and $37 \times 21 \times 118$ cm for Thelonious. The height factor is $h = (\Delta x_f / \Delta x_{7\text{GHz}})^3 = 1$.

Table 2.2: FDTD simulation parameters and computational requirements in FR3 and FR2.

Frequency bands and exposure scenarios						
Frequency [MHz]	Range	Technology	Environmental	Auto-induced		
7000	FR3	6G	✓	✓		
9000	FR3	6G	✓	✓		
11000	FR3	6G	✓	✓		
13000	FR3	6G	✓	✓		
15000	FR3	6G	✓	✓		
26000	FR2	5G NR	✓	–		
Basic quantities: SAR for Thelonious from one direction and 4 cm ² -averaged APD according to IEC/IEEE 63195-2, both normalized to 1 W/m ² .						
Spatial and temporal resolution						
Frequency	Cell size Δx [mm]	Time step Δt [ps]	Skin mesh holes [%]	Cells per δ_{90}	Cells per 10 g side	
7000	0.6	1.16	0	13	36	
9000	0.5	0.96	0	10	43	
11000	0.5	0.96	0	8	43	
13000	0.45	0.87	0	7	48	
15000	0.4	0.77	0	6	54	
26000	0.3	0.58	0	4	72	
Absorption depth and spatial resolution in tissue						
Frequency	δ_{90} eye [mm]	δ_{90} skin [mm]	δ_{90} muscle [mm]	Cells/ λ eye	Cells/ λ muscle	Cells/ λ skin
7000	5.6	–	6.6	9	10	12
9000	3.7	–	4.5	9	10	12
11000	2.7	3.8	3.3	7	9	10
13000	2.1	2.9	2.6	7	8	10
15000	1.7	2.4	2.1	7	8	10
26000	0.8	1.1	1.1	7	8	9
Computational domain size [million cells]						
Frequency	h	Duke	Ella	Eartha	Thelonious reduced	Thelonious half
7000	1.00	750	630	408	268	241
9000	0.58	744	625	404	266	411
11000	0.58	744	625	404	266	411
13000	0.42	742	623	403	265	559
15000	0.30	740	622	401	264	788
26000	1	✗	✗	✗	–	1844

Environmental exposure uses individual plane waves from the stated incidence directions and polarizations. Auto-induced exposure uses equal-gain, phase-only focusing at the user-equipment location. The time step satisfies the Courant limit, and the 10 g cube side is 21.5 mm. Absorption depths refer to the eye-vitreous bottleneck, the 0.5–4 mm skin surface, and bulk muscle. The relative-permittivity ranges for eye, muscle, and skin are 69–31, 57–26, and 46–18. The height factor is $h = (\Delta x_f / \Delta x_{7\text{GHz}})^3$. Reduced domains use $x/2 \times y \times z \cdot h$. Half domains used for SAR use $x/2 \times y \times z$. ✗ indicates simulations not performed.

Table 2.3: ICNIRP 2020 basic restrictions for general public exposure [13].

Quantity	Frequency range	Limit	Avg. time
psSAR _{10g}	< 6 GHz (head/torso)	2 W/kg	6 min
psSAR _{10g}	< 6 GHz (limbs)	4 W/kg	6 min
SAR _{wb}	All frequencies	0.08 W/kg	30 min
APD	> 6 GHz	20 W/m ²	6 min

2.2.1 Frequency selection and technology mapping

The 15 frequencies in Tables 2.1 and 2.2 range from 450 MHz to 26 GHz, covering three spectral regions used by current and future wireless communication systems.

The sub-6 GHz band (FR1) includes nine frequencies representing deployed cellular and Wi-Fi technologies: 450 MHz (LTE Band 31, public safety), 700 MHz (5G NR n28, digital dividend spectrum), 835 MHz (GSM-850), 1450 MHz (LTE Band 32, supplemental downlink), 2140 MHz (LTE Band 1 downlink), 2450 MHz (Wi-Fi 2.4 GHz ISM band), 3500 MHz (5G NR n78, C-band), and 5200/5800 MHz (Wi-Fi 5 GHz UNII bands). These frequencies were selected to sample the most common wireless bands while providing uniform coverage of the RF spectrum up to 6 GHz.

The FR2 band is represented by 26 GHz (5G NR n258). Millimeter-wave bands offer wide contiguous bandwidths (up to 400 MHz per channel), supporting multi-gigabit data rates. High path loss limits practical deployment to short-range, line-of-sight scenarios [30]. For a fixed physical domain and simulation duration, FDTD workload scales approximately as f^4 at a constant number of cells per wavelength. Doubling frequency increases the cell count eightfold and halves the stable time step. A single full-body simulation at 26 GHz with 0.3 mm resolution requires several billion grid cells. Therefore, the analysis at this frequency was limited to one phantom (Thelonious) from one incidence direction.

The upper mid-band (7–15 GHz), also referred to as centimeter wave (cmWave) or part of the prospective FR3 frequency range [2], is sampled at five frequencies: 7, 9, 11, 13, and 15 GHz. This spectrum is under active investigation for 6G systems [1], as it balances the bandwidth limitations of sub-6 GHz bands against the propagation challenges of millimeter-wave frequencies. International regulatory processes are examining spectrum in this range, with the 7.125–8.4 GHz band on the WRC-27 agenda for potential IMT identification [31]. Wider FR3 deployment will increase the importance of APD compliance.

2.2.2 Exposure metrics and normalization

The ICNIRP 2020 guidelines [13] define basic restrictions, which are limits on quantities induced within the body (SAR, APD), and reference levels, which are limits on external field quantities that ensure compliance with basic restrictions

under typical conditions. This study focuses on the former, with the latter as input power density to determine compliance.

For frequencies below 6 GHz, the relevant basic restriction is the peak spatial SAR over any 10 g cubic mass of tissue ($\text{psSAR}_{10\text{g}}$), computed following IEC/IEEE 62704-1 [24]. For frequencies at or above 6 GHz, the basic restriction is the APD averaged over any 4 cm^2 square area, extracted from the skin surface in accordance with IEC/IEEE 63195-2 [25].

All simulations were performed with an incident field amplitude of 1 V/m . Results were subsequently normalized to an incident power density of 1 W/m^2 , corresponding to an electric field amplitude of $E_0 \approx 27.5\text{ V/m}$ in free space. Since SAR scales as E^2 , the normalization factor is $(27.5)^2 \approx 754$. This normalization convention differs from near-field dosimetry, where results are typically normalized to 1 W input power at the antenna feed. For far-field plane-wave illumination, power density is the natural normalization quantity because it is measurable and independent of the source.

2.2.3 Environmental exposure scenario

Figure 2.1a shows the environmental exposure scenario setup. Environmental exposure occurs when ambient electromagnetic fields illuminate a subject from all directions. This scenario applies to non-users exposed to base stations and to technologies like 4G LTE that employ omnidirectional transmission rather than user-specific beamforming. In urban environments with multiple base stations and reflections, incident fields arrive from many directions simultaneously.

To characterize this environmental exposure scenario, plane waves were launched from six orthogonal directions aligned with the phantom's anatomical axes: $\pm x$ (left/right), $\pm y$ (front/back), and $\pm z$ (above/below). For each direction, both θ and ϕ polarizations were simulated, yielding 12 independent FDTD simulations per phantom-frequency combination.

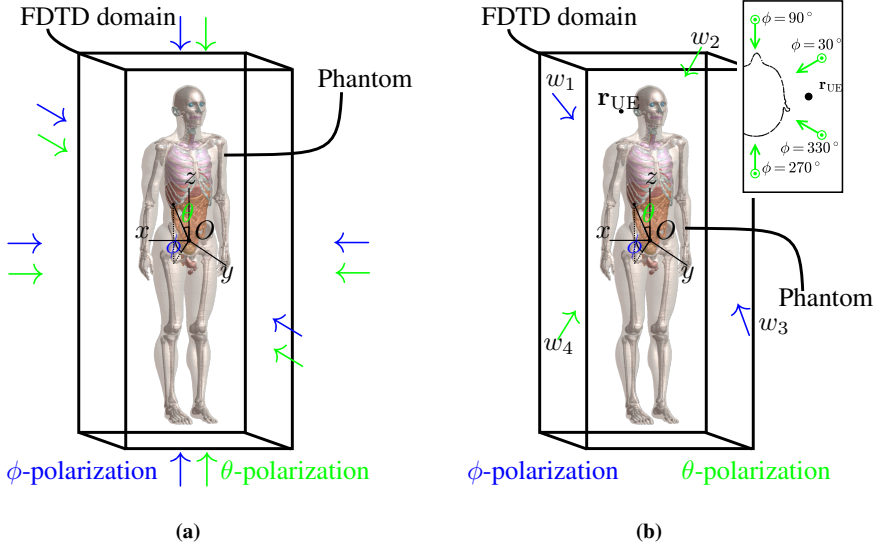


Figure 2.1: Exposure scenarios. (a) Environmental exposure is represented by 12 independent plane waves: six orthogonal directions with two polarizations each. (b) Auto-induced exposure is represented by four equal-amplitude waves whose phases are aligned at the user-equipment location.

The arithmetic mean over these twelve direction–polarization cases is a coarse approximation of directionally distributed exposure. In this chapter, “worst case” means the largest value among the configurations evaluated for the phantom, frequency and exposure model. FR1 environmental maxima are taken over the twelve direction–polarization cases. The environmental FR3/FR2 calculations use the reduced direction sets listed in the tables. Auto-induced maxima are taken over candidate focus points evaluated with the full dosimetric metric after screening. The search does not give a global maximum over incident fields or focus points.

2.2.4 Auto-induced exposure scenario

Figure 2.1b shows the auto-induced exposure scenario with user-specific beamforming. Auto-induced exposure occurs when a MaMIMO base station beamforms toward a user’s device, concentrating electromagnetic energy in a localized hot-spot near the body. Unlike environmental exposure, the incident field exhibits constructive interference at a focal point determined by the beamforming algorithm. 5G NR and anticipated 6G systems use user-specific beamforming to maximize link quality.

Previous work coupled MaMIMO beamforming with site-specific propagation environments. Hybrid ray-tracing and FDTD methods enable realistic exposure assessment for indoor [20, 21] and outdoor [22] scenarios, including stochastic

channel models capturing real propagation statistics. These studies show that exposure depends on environment, user position, and channel realization. We take a different approach: rather than modeling specific environments and aggregating across channel realizations, we seek exposure estimates comparable across phantoms and frequencies without statistical bootstrapping [12, 21].

To simulate this auto-induced exposure scenario, plane waves were launched from four azimuthal directions ($\phi = 270^\circ, 330^\circ, 30^\circ, 90^\circ$) at a fixed co-elevation ($\theta = 90^\circ$), representing a half-space illumination from the phantom's right side. We chose $\theta = 90^\circ$ (horizontal incidence) because base stations are typically mounted at or above head height, making horizontal incidence common, and this geometry maximizes the vertical electric field component E_z . Only θ polarization was considered, as it produces the dominant vertical field component relevant for handheld device coupling [20].

2.2.4.1 Beamforming weights

In MaMIMO systems, MRT is a common precoding technique for beamforming [32]. For a channel vector $\mathbf{h} \in \mathbb{C}^N$ representing the complex gains from N transmit directions to the UE, the MRT precoding vector (Frobenius-normalized) is

$$\mathbf{w} = \frac{\mathbf{h}^*}{\|\mathbf{h}\|}, \quad (2.1)$$

which maximizes the received signal power $|y|^2 = |\mathbf{h}^T \mathbf{w}|^2$ [32]. Writing each channel element in polar form, $h_i = |h_i| \exp(j\phi_i)$, the weight becomes

$$w_i = \frac{|h_i|}{\|\mathbf{h}\|} \exp(-j\phi_i). \quad (2.2)$$

The phase term $\exp(-j\phi_i)$ conjugates the channel phase so that all contributions arrive in phase and interfere constructively at the receiver. The amplitude term $|h_i|/\|\mathbf{h}\|$ allocates more power to directions with stronger channel gains.

In our framework, we interpret each channel h_i as proportional to the vertical electric field component at the UE location due to the i -th incident direction: $h_i \propto E_{z,i}(\mathbf{r}_0)$. We assume the UE antenna is vertically polarized, as is typical for handheld devices. Because each h_i is a per-direction channel in the angular domain rather than a per-antenna channel, this is a beamspace formulation of MRT precoding. The amplitude weighting in (2.2) would require knowledge of which directions have stronger channels, information that depends on the propagation environment.

When simulating many environments using deterministic or stochastic channel models (e.g., ray-tracing or QuaDRiGa [22]) and averaging the resulting exposure over all channel realizations, no single azimuthal direction consistently dominates. All amplitudes are therefore set to $|w_i| = 1/\sqrt{N}$, yielding

$$w_i = \frac{1}{\sqrt{N}} \exp(-j \arg(E_{z,i}(\mathbf{r}_0))). \quad (2.3)$$

With this choice, $\|\mathbf{w}\|^2 = 1$. The weights use MRT phase conjugation with equal amplitudes and form an equal-gain, phase-only approximation to MRT. The combined field at any point $\mathbf{r}$ is then

$$\mathbf{E}_{\text{combined}}(\mathbf{r}) = \sum_{i=1}^N w_i \mathbf{E}_i(\mathbf{r}). \quad (2.4)$$

We assume perfect channel state information and independent phase control of the four incident directions. For these equal amplitudes, phase conjugation maximizes the vertical electric-field component at the selected UE point. The resulting SAR and APD values describe this four-direction exposure scenario.

We use a static channel with perfect channel knowledge and omit tracking errors for a moving UE. With sufficiently frequent channel updates, the focus can follow the UE. Time-averaged exposure therefore depends on channel tracking as well as motion.

Maxwell's equations are linear for the fixed anatomy and amplitude-independent tissue permittivity, conductivity and permeability used here. Equation (2.4) gives the exact field for the chosen combination of incident waves, within the numerical accuracy of the FDTD solutions. SAR and APD are calculated after the complex fields have been added. Each $\mathbf{E}_i$ is a full-wave FDTD solution that already contains the scattering, diffraction, and penetration of wave i into tissue. Therefore, the combined field is defined throughout the body, on the surface and in the interior. $\text{psSAR}_{10\text{g}}$ is then averaged over a 10 g cubic mass inside tissue (IEC/IEEE 62704-1), and APD over a 4 cm² skin-surface area (IEC/IEEE 63195-2). The sum of the individual component power densities equals that of one plane wave. We use this component-power normalization for the comparisons below. Detailed hot-spot field maps are reported in Herssens and Thielens [33] and Shikhantsov *et al.* [20] for the same precoding family and phantoms.

We chose four azimuthal directions for controlled half-space illumination with a manageable number of full-wave simulations. The dominant modes of a particular propagation channel may differ with its angular distribution.

2.2.4.2 Focus point search

Figure 2.2 summarizes the search procedure for the maximum sampled APD. A MaMIMO base station beamforms toward a UE antenna that is held in a hand or pocket and remains in air at some distance from the skin. Therefore, the beamforming focus point lies in the air near the body surface, not inside the body. The beam converges at this air location and illuminates nearby skin, where absorption occurs.

The search space comprises air voxels within a 20 mm shell surrounding the phantom surface. This thickness covers realistic UE-to-body distances while excluding voxels too far to produce substantial skin exposure. From this space, 10,000 candidate focus points were randomly sampled, yielding approximately 10 mm average spacing given the 1.8 m² skin surface area of an adult phantom.

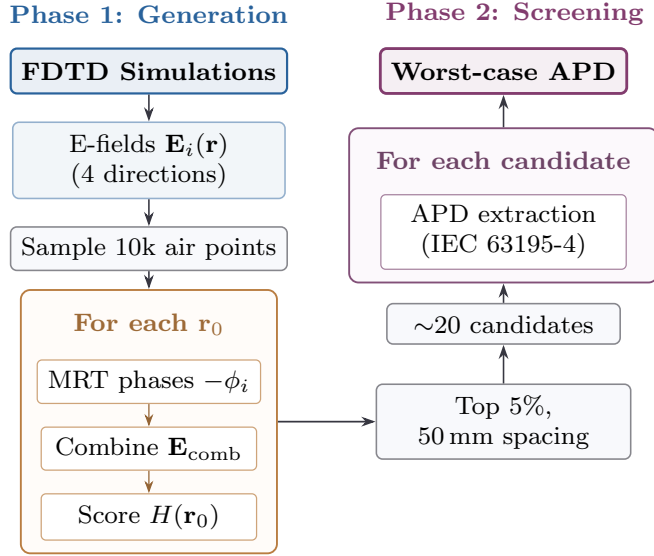


Figure 2.2: Two-stage screening reduces computational cost 500 times. Phase 1 evaluates 10,000 candidates using an efficient hot-spot score based on E-field intensity at nearby skin voxels. Phase 2 performs full APD extraction following IEC/IEEE 63195-2 only on the top 20 candidates.

For FR3 simulations computing only APD, additional padding of 20 mm (x -direction) and 10 mm (y -direction) was added to accommodate focus points behind the phantom (e.g., near the back or arms). At FR1 frequencies (700 MHz and 3500 MHz), the search shell was widened to 50 mm (from 20 mm at FR3). At sub-GHz wavelengths, a beam focused further from the surface still produces a meaningful hot-spot on the skin. The minimum candidate separation was increased to 100 mm, consistent with the $20\times$ longer wavelength at 700 MHz ($\lambda = 430$ mm) compared to FR3. The candidate pool was doubled to 40 per phantom with a lower selection percentile (80% versus 95% at FR3), because the proxy correlation is weaker at these frequencies (see Section 2.3.3). At 3500 MHz and at FR3 frequencies, field combination was restricted to a 50 mm cube around each focus voxel. The SAR peak at these frequencies occurs within millimeters of the focus on the skin surface. At 700 MHz, SAR peaks can appear far from the focus point (see Section 2.3.3), so full-volume combination over the entire body was used instead.

2.2.4.3 Hot-spot score for efficient worst-case identification

We calculate APD for each selected candidate to find the focus point with the highest value. Full APD extraction following IEC/IEEE 63195-2 [25] is computationally expensive: surface integration over 4 cm^2 averaging areas across the entire phantom surface.

We developed the *hot-spot score* that approximates APD without full extraction, exploiting the relationship between electric field intensity and APD. For a given air focus point $\mathbf{r}_0$, the hot-spot score is defined as:

$$H(\mathbf{r}_0) = \frac{1}{N_{\text{skin}}} \sum_{k=1}^{N_{\text{skin}}} |\mathbf{E}_{\text{combined}}(\mathbf{r}_k)|^2, \quad (2.5)$$

The sum includes all N_{skin} skin voxels within a 50 mm cube centered on $\mathbf{r}_0$. We compute $\mathbf{E}_{\text{combined}}$ from Eq. (2.4), using the weights for $\mathbf{r}_0$ from Eq. (2.3).

The hot-spot score works because $\text{APD} \propto \sigma |\mathbf{E}|^2$, where σ is the tissue conductivity. Computing the hot-spot score requires only reading pre-computed E-field values at skin voxel locations and performing the weighted combination. No additional FDTD simulations or surface integrations are needed. This enables rapid evaluation of all 10,000 candidate focus points. We kept candidates in the top 5% by hot-spot score for full APD extraction. To avoid clustering, a minimum separation of 50 mm was enforced: candidates were selected greedily in descending hot-spot score order, skipping any candidate within 50 mm of an already-selected point.

2.2.5 Numerical simulation framework

2.2.5.1 Solver and automation

We performed all simulations using Sim4Life 8.2 [34], a GPU-accelerated FDTD solver based on the Yee algorithm [35, 36]. We terminated the computational domain with seven uniaxial perfectly matched layer (UPML) absorbing layers. We used the total-field/scattered-field (TF/SF) formulation [36] for far-field illumination. All sources were harmonic excitations at frequencies listed in Tables 2.1 and 2.2, with 1 V/m incident amplitude. Simulation duration was three times the domain diagonal traversal time in free space (6 cycles at 450 MHz, 500 cycles at 26 GHz).

Given the study scale (550 simulations across 15 frequencies, 4 phantoms, multiple directions and polarizations), we developed an open-source Python framework automating the simulation workflow. Each simulation is defined by a JSON configuration file for reproducibility.

2.2.5.2 Computational methodology

Spatial discretization used a frequency-dependent scheme: 2.5 mm cells at 450–1450 MHz (10–32 cells per wavelength (CPW) in vitreous humor), reducing to 1.0–1.7 mm at 2140–5800 MHz, and 0.3–0.6 mm at FR3 frequencies. Time stepping followed the Courant–Friedrichs–Lewy (CFL) stability limit [37] ($\Delta t = \Delta x_{\text{min}}/(c_0\sqrt{3})$). The resulting time steps range from 4.81 ps at 450 MHz to 0.58 ps at 26 GHz. Grid resolution was chosen to balance numerical accuracy (targeting 10 CPW in high-permittivity tissues), skin mesh perforation (minimized at $\Delta x \leq 1.5$ mm), and computational cost (scaling with the fourth power of cell size without domain reduction). The 90% power absorption depth (δ_{90}) decreases

from ~ 60 mm in muscle at 450 MHz to 1.1 mm in skin at 26 GHz, justifying coarser grids at low frequencies where penetration is deep. At sub-6 GHz frequencies, absorption extends beyond the skin.

2.2.5.3 Anatomical phantoms

We used four anatomically realistic human body models from the ViP of the IT'IS Foundation [23]: two adults and two children, one for each sex. The ViP models (version 3.1) have $500\text{ }\mu\text{m}$ isotropic native resolution throughout the body. Duke (adult male, 34y) and Ella (adult female, 26y) represent adults. Thelonious (male, 6y) and Eartha (female, 8y) represent children. Each phantom comprises over 300 anatomical structures with tissue-specific dielectric properties. Frequency-dependent dielectric properties (ϵ_r , σ) and mass density values came from the IT'IS tissue properties database (version 5) [38].

In addition to whole-body and peak spatial-average SAR, regional SAR was computed for four anatomical groups relevant to RF exposure assessment: the brain, eyes, skin, and genitals. These regions appear frequently in epidemiological studies and regulatory discussions. Regional SAR is defined as the mass-weighted average of SAR values across all tissues in the group. The *brain group* comprises gray matter, white matter, cerebellum, hippocampus, thalamus, hypothalamus, midbrain, pons, medulla oblongata, hypophysis, pineal body, commissura anterior, commissura posterior, and cerebrospinal fluid. The *eyes group* comprises the cornea, lens, sclera, and vitreous humor. The *skin group* comprises, as defined by Sim4Life, the skin and “Ear skin” entities. The *genitals group* comprises sex-specific reproductive organs. For male phantoms (Duke, Thelonious) it includes testis, epididymis, prostate, and penis. For female phantoms (Ella, Eartha) it includes ovary, uterus, and vagina.

2.2.6 Computational efficiency strategies

At FR3 and FR2 frequencies, fine grid resolution produces computational domains with hundreds of millions to billions of cells. Two domain reduction strategies and cloud infrastructure made these simulations tractable.

2.2.6.1 Sagittal half-domain reduction

For one-sided high-frequency incidence, the domain was truncated at the sagittal midplane and terminated with a perfectly matched layer (PML). This reduces the computational domain by approximately half. The approximation relies on weak coupling through the body to the omitted side. The “ $x/2$ ” notation in Table 2.2 indicates this reduction. Metrics for tissues crossing the cut are excluded where the reduction is used (Section 2.3.2).

2.2.6.2 Height factor reduction

Above 7 GHz, domain height was further reduced by a frequency-dependent height factor h . We chose 7 GHz as the reference because at this frequency the domain reaches approximately 800 million cells for adult phantoms, a practical limit beyond which GPU memory becomes limiting, even in multi-GPU configurations. The height reduction starts by removing the lower body (feet and legs), as peak absorption in the auto-induced scenario occurs in the head and upper torso region.

The height factor was computed as:

$$h = \left(\frac{\Delta x_f}{\Delta x_{7 \text{ GHz}}} \right)^3, \quad (2.6)$$

where Δx_f is the cell size at frequency f and $\Delta x_{7 \text{ GHz}} = 0.6 \text{ mm}$ is the reference cell size at 7 GHz. This cubic scaling keeps the number of grid cells roughly constant as frequency increases: the cell counts for Duke, Ella, Eartha, and Thelonious remain within 2% of their 7 GHz values across the entire FR3 band (Table 2.2). At 15 GHz, for example, $h = (0.4/0.6)^3 \approx 0.30$, meaning only the top 30% of the phantom height is simulated.

We compared full-body and reduced-height simulations for Duke and Thelonious under θ -polarized broadside plane-wave incidence. Removing the lower 70% changed local peak SAR by at most 3.5% at 3.5 GHz and 1.4% at 7 GHz. Height reduction is used only above 7 GHz.

Without this height reduction, simulations at 15 GHz would require approximately 2.8 billion cells per phantom, over three times the 7 GHz baseline. The time step also decreases with frequency (from 1.16 ps at 7 GHz to 0.77 ps at 15 GHz), adding to the computational cost. For the 26 GHz simulation, the height factor approach was not applied ($h = 1$) to compute SAR_{wb} . Instead, only the smallest phantom (Thelonious) was simulated from a single incidence direction, using sagittal half-domain reduction. These simulations use the full body height. The whole-body average uses the full-body mass and assumes negligible absorption in the omitted sagittal half. The same single-direction approach was used for Thelonious at FR3 frequencies to allow SAR extraction for comparison with APD (“Half (for SAR)” entries in Table 2.2). Even with these simplifications, the 26 GHz simulation required 1.84 billion cells and multiple 48 GB GPUs.

2.2.6.3 Computational resources and campaign scale

We executed simulations on rented cloud GPU instances (TensorDock) with NVIDIA H100, RTX 5090, and RTX 6000 GPUs, sometimes in multi-GPU workstations, paired with 32–256 GB RAM. Cloud infrastructure was chosen over traditional high-performance computing (HPC) because our HPC options impose quotas and queues, and Sim4Life requires Windows with licensing better suited to workstations.

The campaign comprised 550 individual FDTD runs across all phantom-frequency-direction-polarization combinations. Simulations ranged from 11 million

cells (Thelonious at 450 MHz) to 1.84 billion cells (Thelonious at 26 GHz). Computational cost varied considerably due to f^4 scaling. Duke at 450 MHz completes in under 5 minutes, at 5.8 GHz in 25 minutes, and at 26 GHz (Thelonious only, half-body) in over 2 hours, at which point I/O-bound setup and extraction phases took similar time.

At high frequencies, a fine surface region with a coarser interior could reduce costs. However, this brings problems related to subgridding, including stability [39]. Such reductions require attention to tissue interfaces, absorbing boundaries and the absorbed-power-density maximum. Chapter 5 develops a surface absorption model.

2.3 Results

The simulations produced a large multi-dimensional dataset. This section summarizes the main findings.

For comparison with ICNIRP basic restrictions for general public exposure, the limits are 0.08 W/kg for whole-body average SAR, 2 W/kg for local psSAR_{10g} (head and trunk), and 20 W/m² for APD above 6 GHz (Table 2.3).

2.3.1 FR1 environmental exposure

All SAR values in this section are normalized to an incident power density of 1 W/m². The ICNIRP 2020 reference levels for general public exposure are $S_{\text{ref}} = f_{\text{MHz}}/200$ W/m² for frequencies below 2 GHz, and 10 W/m² at 2 GHz and above. SAR values can be scaled by these factors to obtain values at the reference level.

2.3.1.1 Penetration depth determines the frequency response

Figure 2.3 shows the normalized SAR as a function of frequency. The 90% power absorption depth (δ_{90}) on the body decreases from ~ 60 mm at 450 MHz to ~ 10 mm at 5800 MHz. This shift from volumetric to superficial absorption explains the frequency dependence of all SAR metrics.

Figure 2.3 shows opposite trends for different tissue groups. Skin SAR increases by a factor of 3.2 between 450 MHz and 5800 MHz, as energy concentrates superficially. Brain SAR decreases by 96% between 450 MHz and 5800 MHz, because skull and overlying tissues absorb most energy before it reaches the brain. Whole-body SAR decreases by a factor of 2.1 between 450 MHz and 5800 MHz, because total absorbed power decreases when absorption is confined to a thin surface layer.

Figure 2.4 shows the transition in the brain-to-skin SAR ratio across all phantoms. At 450 MHz, the ratio ranges from 0.74 to 1.05, meaning brain and skin SAR are comparable. As frequency increases, the ratio drops significantly for all phantoms. At 5800 MHz, the ratios decrease to between 0.003 and 0.015. Child phantoms maintain higher relative penetration at high frequencies compared to

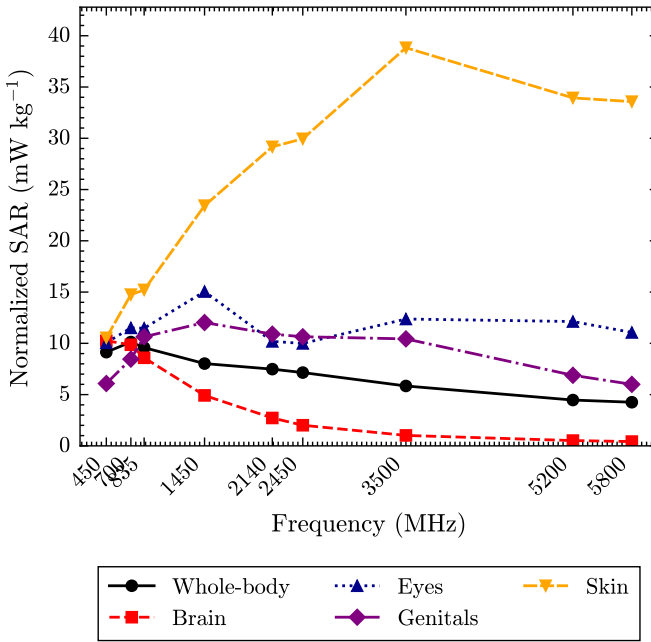


Figure 2.3: Skin SAR increases 3.2 times while brain SAR decreases 96% across FR1. Mass-averaged SAR by tissue group for Thelonious, averaged across all 12 directions and polarizations. Eyes show a non-monotonic response.

adults. This two-order-of-magnitude decrease across the FR1 band shows the shift from penetrating to superficial absorption.

2.3.1.2 Tissue-specific absorption

Figure 2.5 ranks the 20 tissues with highest mass-averaged SAR, averaged across all frequencies and directions. Ear cartilage (36.9 mW/kg) and ear skin (29.5 mW/kg) absorb significantly more power per unit mass than bulk skin (21.5 mW/kg). Their peripheral position and thin geometry explain this: the pinna is exposed from multiple directions and lacks underlying tissue to absorb incident energy.

Cornea ranks fifth (16.8 mW/kg), consistent with the eye’s exposed position. Testis ranks ninth (12.2 mW/kg), receiving substantial frontal exposure despite pelvic shielding from other angles. Meniscus ranks tenth (11.5 mW/kg). Inside the skull, cerebrospinal fluid (CSF) ranks eighth (12.5 mW/kg), higher than gray matter (5.6 mW/kg) and white matter (3.2 mW/kg), because of its high water content and conductivity.

For $\text{psSAR}_{10\text{g}}$, the 10 g averaging volume smooths tissue-specific variations. Skin dominates (83.5 mW/kg), followed by subcutaneous fat (81.4 mW/kg), muscle (75.7 mW/kg), and bone (73.7 mW/kg). Small tissues such as ear cartilage (7 g

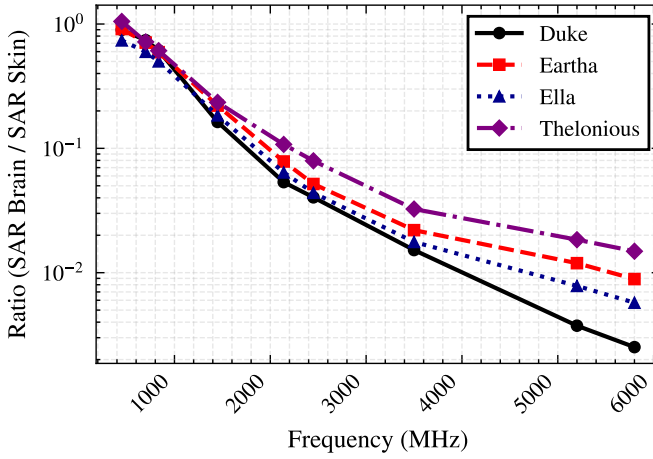


Figure 2.4: Brain-to-skin SAR ratio across phantoms. Brain exposure drops by orders of magnitude relative to skin as frequency increases. Child phantoms show higher relative brain exposure at high frequencies compared to adults.

total mass) cannot fill a 10 g cube and thus do not appear in the $\text{psSAR}_{10\text{g}}$ ranking.

2.3.1.3 Children have higher whole-body SAR than adults

Figure 2.6 compares whole-body SAR across phantoms. Child phantoms (Thelonious, 6y, and Eartha, 8y) show 1.5–1.9 times as high SAR_{wb} as adults (Duke, Ella) at all frequencies. At 700 MHz, Thelonious reaches 10.1 mW/kg versus Duke’s 5.5 mW/kg (ratio 1.85).

The higher whole-body SAR in children follows from the relationship between SAR, absorption cross section (ACS), and body mass [40]:

$$\text{SAR}_{\text{wb}} = \frac{\text{ACS}_{\text{wb}} \times S}{m} \quad (2.7)$$

where ACS_{wb} is the whole-body absorption cross section (in m^2), S is the incident power density, and m is body mass. Although children have smaller ACS_{wb} than adults (less body surface area), their mass is proportionally much smaller. The ratio ACS_{wb}/m is approximately 50% higher in a 6-year-old than in an adult, meaning children absorb more power per kilogram of body mass. At sub-GHz frequencies, body dimensions approach fractions of the wavelength ($\lambda = 43$ cm at 700 MHz), potentially producing quasi-resonance effects that differ between body sizes.

2.3.1.4 Direction and polarization dependence

Table 2.4 summarizes directional variation for each SAR metric (Thelonious, frequency-averaged values). Similar patterns are observed for the other phantoms: frequency-averaged whole-body SAR varies $2.0\text{--}2.3\times$ across phantoms,

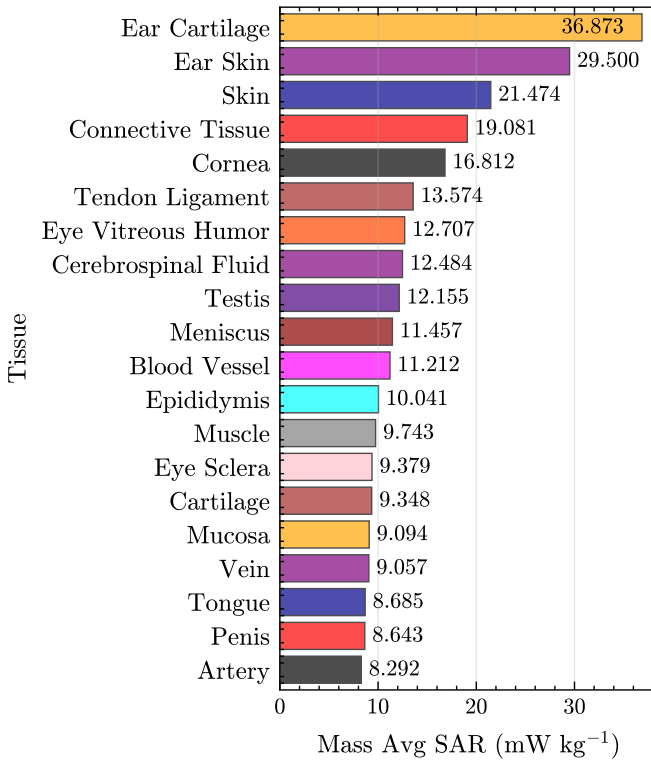


Figure 2.5: Ear tissues absorb twice as much power per unit mass as bulk skin. Top 20 tissues ranked by mass-averaged SAR for Thelonious, averaged across all frequencies in FR1 and directions. Cornea, testis, and meniscus also rank in the top 10.

skin 4.5–6.4 $\times$, eyes 20–36 $\times$, and brain 3.6–6.0 $\times$. Genitals show the largest inter-phantom difference in directional variation, ranging from 9–10 $\times$ for females (Ella, Eartha) to 46–67 $\times$ for males (Duke, Thelonious). For Thelonious, eyes show 20-fold variation: frontal exposure yields 28.9 mW/kg versus 1.4 mW/kg from behind, as the cornea is exposed while the skull shields posteriorly. Genitals show 44-fold variation between frontal and below directions. The body shields the pelvic region from most angles. Brain SAR shows a fourfold variation because the skull shields the brain from all directions. Whole-body SAR varies 2-fold.

Polarization generally has a smaller effect than direction. Figure 2.7 shows the polarization ratio for different tissue groups and incident directions. The θ/ϕ polarization ratio ranges from 0.8 to 1.6 for skin and whole-body SAR. Genitals are an exception. From below, the ratio reaches 1.8, indicating stronger coupling to vertically polarized fields. From above, it drops to 0.12. The results may be underestimated because material properties from the IT'IS database are isotropic.

The IT'IS database also assigns age-independent dielectric properties. The child

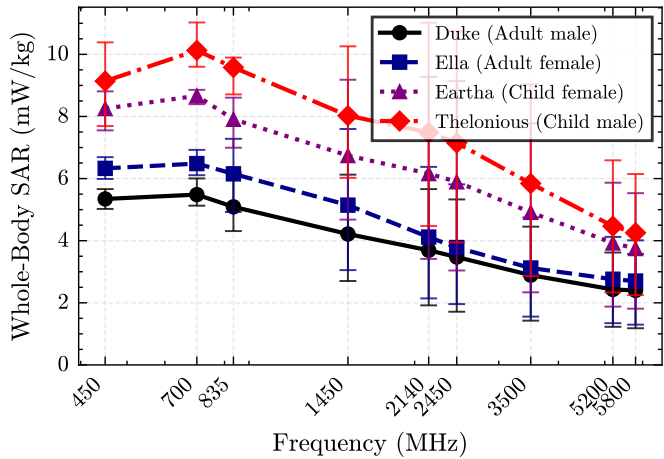


Figure 2.6: Children show 1.5–1.9 times as high whole-body SAR as adults at all frequencies. Error bars show the standard deviation across the twelve simulated direction–polarization cases for each phantom. Numerical and input uncertainty are assessed separately in the modelling budget.

Table 2.4: Directional variation in SAR metrics (Thelonious, frequency-averaged values).

Metric	Max (mW/kg)	Min (mW/kg)	Max/Min
Eyes SAR	28.9 (front)	1.4 (back)	20×
Genitals SAR	30.5 (front)	0.7 (below)	44×
Brain SAR	6.5 (below)	1.8 (above)	4×
Skin SAR	41.3 (front)	9.2 (above)	4×
Whole-body SAR	10.3 (back)	5.3 (below)	2×

phantoms therefore have child anatomy but adult tissue properties. Age-independent properties are standard in numerical dosimetry [9, 10, 23]. A closed-form Fresnel analysis shifts the APD and whole-body SAR conservatively, by 6–10%. This shift is comparable to the 4–9% that a 10–20% dielectric-parameter uncertainty propagates onto the same metrics. This sensitivity affects the interpretation of the near-threshold APD results at 7 GHz.

We collect these effects into one uncertainty budget. The dominant random contributions are the tissue-dielectric spread and the FDTD numerical error. Combined in quadrature, they give an expanded uncertainty of about $\pm 12\%$ on the absorbed-power metrics, at a 95% coverage probability. The age and domain-truncation effects act in one direction, conservatively.

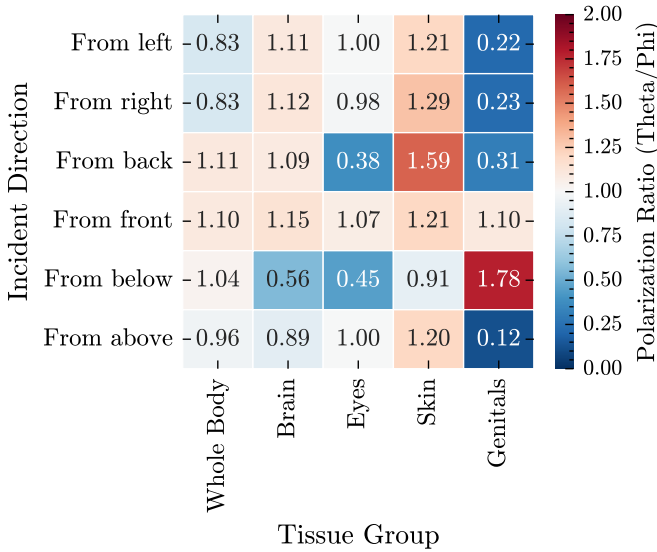


Figure 2.7: Polarization ratio (θ/ϕ) for different tissue groups and incident directions. Values near 1 indicate insensitivity. Genitals show strong polarization sensitivity (ratio = 1.8 from below). Whole-body SAR remains insensitive.

2.3.1.5 Correlation between SAR metrics

The correlation matrix across all 432 simulation configurations shows that most metrics are independent, with one protective effect. Skin SAR and brain SAR correlate negatively ($r = -0.45$, $p < 0.001$): high skin absorption reduces energy available for deeper penetration. Superficial absorption shields deep tissues.

Whole-body SAR and skin SAR are nearly uncorrelated ($r = -0.04$). At low frequencies, deep tissues (muscle, organs) dominate whole-body SAR. At high frequencies, whole-body SAR decreases even as the skin fraction increases. These opposing trends cancel.

psSAR_{10g} values for different organs are largely independent. Skin and genitals correlate at only $r = 0.14$. Brain and eyes correlate at $r = 0.54$ (both head-region metrics). Worst-case exposure for one organ does not predict the worst case for another organ.

2.3.1.6 Compliance margins at reference levels

Table 2.5 compares direction-averaged SAR at the ICNIRP reference levels against the basic restrictions. The reference level S_{ref} increases from 2.25 W/m² at 450 MHz to 10 W/m² at 2 GHz and above. The rightmost column shows the percentage of the basic restriction reached by the maximum SAR value across all four phantoms.

Table 2.5: Direction-averaged whole-body SAR at ICNIRP reference levels (FR1).

Freq (MHz)	S_{ref} (W/m ²)	Duke (M,34y)	Ella (F,26y)	Eartha (F,8y)	Thelonious (M,6y)	% of limit ^a
Direction-averaged SAR _{wb} (mW/kg)						
450	2.25	12.0	14.2	18.6	20.6	26%
700	3.50	19.2	22.7	30.3	35.5	44%
835	4.18	21.3	25.7	33.1	40.0	50%
1450	7.25	30.5	37.3	48.9	58.2	73%
2140	10.0	36.9	41.2	61.6	74.8	93%
2450	10.0	34.7	37.8	59.0	71.5	89%
3500	10.0	28.9	31.2	49.1	58.4	73%
5200	10.0	24.3	27.6	39.3	44.7	56%
5800	10.0	24.0	27.0	37.5	42.6	53%

^aMaximum across all four phantoms. Basic restriction SAR_{wb} = 80 mW/kg.

Whole-body SAR peaks near 2140 MHz for all phantoms, giving the tightest compliance margin in the FR1 band. Thelonious reaches 93% of the basic restriction at this frequency. Child phantoms (Thelonious, Eartha) exceed adults by a factor of 1.7–1.9 across all frequencies. Sex accounts for less than 20% variation within each age group. Adult phantoms remain below 52% of the basic restriction at all frequencies.

These values are averaged over the 12 directions. The worst single configuration (front or back incidence) is 1.5–1.6 times as high. Under that configuration both child phantoms exceed the basic restriction near 2140 MHz. Thelonious is at 145% of the limit and Eartha at 122%. Four of the twelve configurations exceed the limit for each of them. Duke and Ella are below 82% in every configuration.

These values occur at the ICNIRP reference level. A ten-country measurement campaign found environmental power densities of 0.33–1.72 mW/m², three to four orders of magnitude below the 10 W/m² reference level [41]. At the highest measured level, the worst configuration for Thelonious is 4000 times below the basic restriction.

For psSAR_{10g}, margins are substantially larger. Skin psSAR_{10g} reaches 909 mW/kg at 2140 MHz for Duke at the reference level (45% of the 2000 mW/kg limit). Brain and eyes psSAR_{10g} reach 178 mW/kg and 137 mW/kg, respectively (9% and 7% of the limit). These are direction-averaged values as well. In the worst configuration, Eartha is at 129% of the 2 W/kg head and torso restriction at 2140 MHz. The peak is located in the hand, where the limb restriction of 4 W/kg applies instead. Against that restriction, Eartha is at 65%. psSAR_{10g} is therefore below its applicable restriction in every environmental configuration. For FR1 environmental exposure, whole-body SAR is the limiting metric for both the average and maximum over the twelve direction–polarization cases.

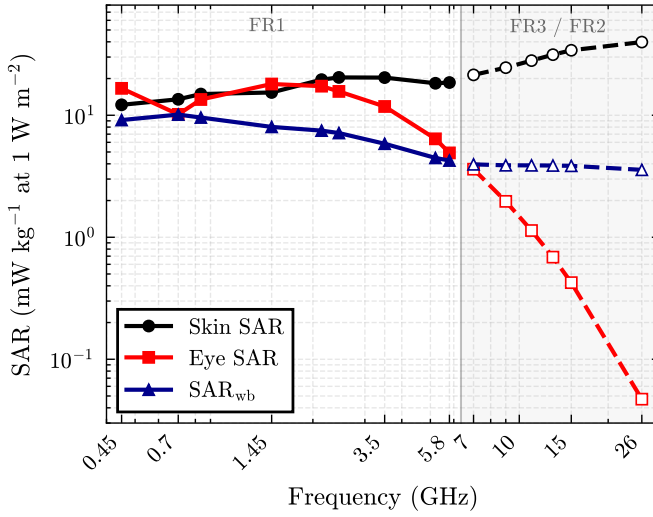


Figure 2.8: Eye SAR decreases 77-fold from 7 to 26 GHz as penetration depth falls below eyelid thickness. Skin SAR rises through the full band. Mass-averaged SAR for Thelonious. Solid lines: FR1. Dashed lines: FR3 and FR2. Skin and eye SAR: right-side illumination throughout. Whole-body SAR: FR1 solid = average over the twelve direction–polarization cases, FR3/FR2 dashed = single right-side direction. Brain and genitals SAR are excluded due to PML boundary artifacts in the FR3 half-phantom.

2.3.2 SAR trends extended to FR3 and FR2

All SAR values in this section are normalized to 1 W/m^2 incident and cover Thelonious (M, 6y) under right-side illumination (θ polarization) at 7–26 GHz. Brain SAR is excluded: structures at the sagittal cut face of the half-phantom show SAR increasing with frequency, opposite to the physical expectation for deep tissue (PML boundary artifact). Genitals SAR is excluded by the same mechanism: the penis and prostate run along the sagittal midplane and are cut and exposed to the PML face.

2.3.2.1 Skin and eye SAR across the full band

Figure 2.8 shows skin SAR, eye SAR, and whole-body SAR from 450 MHz to 26 GHz. Skin SAR continues to rise: 18.6 mW/kg at 5800 MHz (FR1, right-side), 21.5 mW/kg at 7 GHz, and 39.8 mW/kg at 26 GHz. The δ_{90} on the body falls from ~ 10 mm at 5800 MHz to 1.1 mm in skin at 26 GHz, concentrating absorption in a progressively thinner surface layer.

Eye SAR falls from 4.92 mW/kg at 5800 MHz to 3.62 mW/kg at 7 GHz, then to 0.047 mW/kg at 26 GHz, a 77-fold decrease across FR3 and FR2. The Thelonious phantom has closed eyes. The eyelid skin covers the cornea. At 26 GHz, δ_{90} in skin

falls to 1.1 mm, comparable to eyelid thickness, and incident energy is absorbed in the eyelid before reaching the cornea. The FR1/FR3 boundary is smooth for both skin and eye SAR. Whole-body SAR is normalized by the full-body mass. The shadow half absorbs only the diffraction from the plane wave, limited at 7 GHz, so the illuminated half carries the body's absorbed power. The value is 4.0 mW/kg at 7 GHz (single direction), continuous with the 4.3 mW/kg 12-direction average at 5800 MHz. The whole-body SAR stays flat near 3.6–4.0 mW/kg across FR3 and FR2.

2.3.2.2 psSAR continuation

psSAR_{10g} connects smoothly at the band boundary: 63.5 mW/kg at 5800 MHz, 60.4 mW/kg at 7 GHz, and 50.3 mW/kg at 26 GHz. The decrease is 21% from 5800 MHz to 26 GHz. Spatial averaging over 10 g smooths the increasingly confined surface absorption. As energy concentrates in a thinner layer, the peak spread over a fixed 10 g volume changes slowly. At 5800 MHz, the maximum psSAR_{10g} over the twelve tested direction–polarization cases is approximately 116 mW/kg, roughly twice the right-side single-direction value. FR3 and FR2 values use a single direction. The maximum over other directions was not evaluated.

2.3.3 FR1 auto-induced exposure

All values are normalized to 1 W/m² incident and scale proportionally at the reference level ($S_{\text{ref}} = 3.5 \text{ W/m}^2$ at 700 MHz, 10 W/m² at 3500 MHz). ICNIRP (2020) basic restrictions for local SAR are psSAR_{10g} = 2 W/kg (head/torso) and 4 W/kg (limbs). For whole-body exposure, SAR_{wb} = 80 mW/kg.

2.3.3.1 psSAR at 700 MHz and 3500 MHz

Table 2.6 compares auto-induced and environmental psSAR_{10g} and SAR_{wb} at both frequencies. At 3500 MHz, auto-induced psSAR_{10g} exceeds the basic restriction for all four phantoms at the reference level. The highest evaluated values reach 131–158% of the 2 W/kg head/torso limit, with the SAR peak located in the torso, chest, or neck for all four phantoms. At 700 MHz, all phantoms comply. Duke and Eartha peak in the lower leg, where the 4 W/kg limb limit applies, reaching 22% and 30% respectively. Ella and Thelonious peak in the torso (49% and 48% of the 2 W/kg limit).

For 3500 MHz, the environmental value for Thelonious already reaches 98% of the basic restriction at S_{ref} , and beamforming causes non-compliance for all four phantoms. This scenario uses simplified MRT beamforming from four directions and is not an upper bound. Coherent array gain grows with the number of antenna elements [42]. Richer propagation environments provide more multipath components for constructive interference, so higher local SAR values are physically feasible. Real deployments vary beam direction with user movement and channel

Table 2.6: Auto-induced $\text{psSAR}_{10\text{g}}$ and SAR_{wb} compared to the maximum environmental value over the twelve tested cases. All values at 1 W/m^2 incident. The % limit column gives $\text{psSAR}_{10\text{g}}$ as a percentage of the applicable local-SAR basic restriction at S_{ref} .

Phantom	700 MHz ($S_{\text{ref}} = 3.5 \text{ W/m}^2$)					3500 MHz ($S_{\text{ref}} = 10 \text{ W/m}^2$)		
	$\text{psSAR}_{10\text{g}}$ [mW/kg]		SAR_{wb} [mW/kg]		% limit at S_{ref}	$\text{psSAR}_{10\text{g}}$ [mW/kg]		% limit at S_{ref}
	Env.	Auto.	Env.	Auto.		Env.	Auto.	
Duke (M, 34y)	129	253	6.7	6.5	22% ^a	156	266	133% ^b
Eartha (F, 8y)	173	339	11.2	11.6	30% ^a	159	305	152% ^b
Ella (F, 26y)	168	280	8.3	7.5	49%	135	316	158% ^b
Thelonious (M, 6y)	132	275	12.4	11.7	48%	197	262	131% ^b

^aPeak in lower leg. Limb limit (4 W/kg) applies.

^bPeak in torso/chest/neck. Head/torso limit (2 W/kg) applies.

dynamics (e.g., with time-division multiple access (TDMA)), which can reduce time-averaged exposure.

These values occur at the ICNIRP reference level. A ten-country measurement campaign found $2.61\text{--}11.12 \text{ mW/m}^2$ at 3500 MHz under continuous worst-case downloading, three orders of magnitude below that level [41]. Realistic exposure is well below the basic restrictions.

At 700 MHz, the environmental value is well within compliance, and beamforming roughly doubles $\text{psSAR}_{10\text{g}}$ with ample margin to the limit. For the evaluated focus points, local SAR stays below 49% of the basic restriction at the reference level. The weak proxy correlation at 700 MHz (Section 2.3.3.2) means other focus points may give higher values.

SAR_{wb} at 700 MHz is essentially unchanged by beamforming. Auto-induced SAR_{wb} ranges $6.5\text{--}11.7 \text{ mW/kg}$ across phantoms at 1 W/m^2 , within the spread of environmental values ($4.1\text{--}12.4 \text{ mW/kg}$ across the 12 directions). Coherent focusing redistributes absorption spatially without increasing total absorbed power.

2.3.3.2 Proxy reliability and candidate search

The hot-spot-score proxy agrees with the APD ranking in the evaluated FR3 candidate sets. It performs differently across the two FR1 frequencies. At 3500 MHz, Spearman rank correlation between proxy score and $\text{psSAR}_{10\text{g}}$ ranges from $\rho = 0.70$ to 0.80 ($p < 0.001$) across phantoms. The worst-case candidate ranks within the top 8 for all phantoms (top 2 for Duke and Ella, top 1 for Thelonious).

At 700 MHz, rank correlation drops to $\rho = 0.27\text{--}0.42$. Duke's worst case ranks 36th of 40 by proxy score. At this frequency ($\lambda = 430 \text{ mm}$), body dimensions approach resonance, diffraction wraps fields around the body, and the SAR peak location decouples from the beam focus point. Duke illustrates the effect: the focus voxel lies in the head region, yet the SAR peak occurs in the lower leg (10% of body height). The proxy predicts near-surface field concentration but not deep-tissue

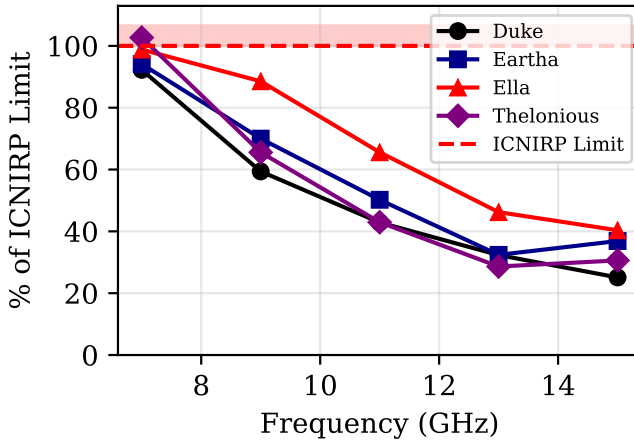


Figure 2.9: Auto-induced APD as a percentage of the basic restriction at the 10 W/m² reference level. Thelonious reaches 103% at 7 GHz, with the $\pm 12\%$ expanded modelling uncertainty overlapping the limit. The shaded region marks values above 100%. At 15 GHz, all phantoms are below 40%.

absorption at sub-GHz wavelengths. A larger candidate pool of 40 per phantom compensated for the proxy’s weak discriminating power at 700 MHz.

2.3.4 FR3 auto-induced exposure

All APD values in this section are normalized to an incident power density of 1 W/m². At the ICNIRP reference level of 10 W/m² (applicable above 2 GHz), values scale by a factor of 10. The basic restriction is APD = 20 W/m² averaged over 4 cm².

2.3.4.1 Near-threshold APD at 7 GHz

Figure 2.9 shows each phantom’s APD as a percentage of the basic restriction across the FR3 band. Thelonious reaches an APD of 20.5 W/m² at 7 GHz, or 103% of the 20 W/m² basic restriction after rounding. The $\pm 12\%$ expanded modelling uncertainty gives a range of approximately 18.0–23.0 W/m². Therefore, the result is near the threshold and the excess is smaller than the estimated uncertainty. Previous studies have reported exceedances of basic restrictions when reference levels are met, particularly for small children at lower frequencies [11].

At 7 GHz, all phantoms reach 90% or more of the basic restriction: Duke (92%), Eartha (94%), Ella (99%), and Thelonious (103%). Compliance margins improve at higher frequencies: at 15 GHz, all phantoms fall below 40% of the basic restriction. The wavelength-to-averaging-area relationship explains this: at 7 GHz ($\lambda = 43$ mm), the MRT-focused beam forms a hot-spot comparable to the 4 cm²

Table 2.7: Highest evaluated APD by phantom and frequency (W/m^2 at $1 \text{ W}/\text{m}^2$ incident).

Phantom	7 GHz	9 GHz	11 GHz	13 GHz	15 GHz
Duke	1.84	1.19	0.86	0.65	0.50
Ella	1.98	1.77	1.31	0.92	0.81
Eartha	1.88	1.40	1.00	0.65	0.74
Thelonious	2.05	1.31	0.86	0.57	0.61

averaging area, maximizing averaged power density. At 15 GHz ($\lambda = 20 \text{ mm}$), the smaller hot-spot size spreads power over less of the averaging region.

2.3.4.2 Peak APD decreases with frequency

Table 2.7 lists the highest evaluated APD for each phantom-frequency combination. Peak APD decreases $3\text{--}4\times$ from 7 GHz to 15 GHz for all phantoms. Thelonious shows the highest value at 7 GHz ($2.05 \text{ W}/\text{m}^2$ at $1 \text{ W}/\text{m}^2$ incident). Duke shows the lowest ($1.84 \text{ W}/\text{m}^2$). The child-to-adult ratio is approximately 1.1 at 7 GHz, smaller than the 1.5–1.9 ratio for whole-body SAR in FR1.

2.3.4.3 MRT focuses the vertical field component

Four-direction MRT beamforming generates constructive interference along the vertical (z) axis. Peak E_z at the hot-spot is approximately $1.8 \text{ V}/\text{m}$ at $1 \text{ W}/\text{m}^2$ incident. E_x and E_y are $0.8\text{--}0.9 \text{ V}/\text{m}$. The vertical component is thus $2\times$ stronger than horizontal components, as expected for vertical UE antenna orientation.

Hot-spot locations distribute across torso, neck, and head. Torso shows highest hot-spot scores ($\sim 250\text{--}315 \text{ V}^2/\text{m}^2$). Extremities (feet, hands) show $5\times$ lower values ($\sim 40\text{--}80 \text{ V}^2/\text{m}^2$). All four phantoms exhibit this pattern.

2.3.4.4 Hot-spot score predicts APD

Figure 2.10 shows the relationship between hot-spot score (Eq. (2.5)) and measured APD for all $20 \times 4 \times 5 = 400$ candidate hot-spots. Linear regression yields

$$\text{APD} = 0.0050 \times H + 0.16 \quad (R^2 = 0.79, p \approx 0) \quad (2.8)$$

where H is the hot-spot score in V^2/m^2 and APD is in W/m^2 .

Equation (2.8) is an empirical fit across different frequencies, phantoms and focus locations at a fixed incident power density. For any fixed configuration, both H and APD scale with incident power and vanish at zero incident field. Their ratio varies across configurations because they use different spatial averaging and loss weighting. A fitted line across these configurations can therefore have a nonzero intercept. The fit should be used within the sampled H range, approximately $42\text{--}363 \text{ V}^2/\text{m}^2$.

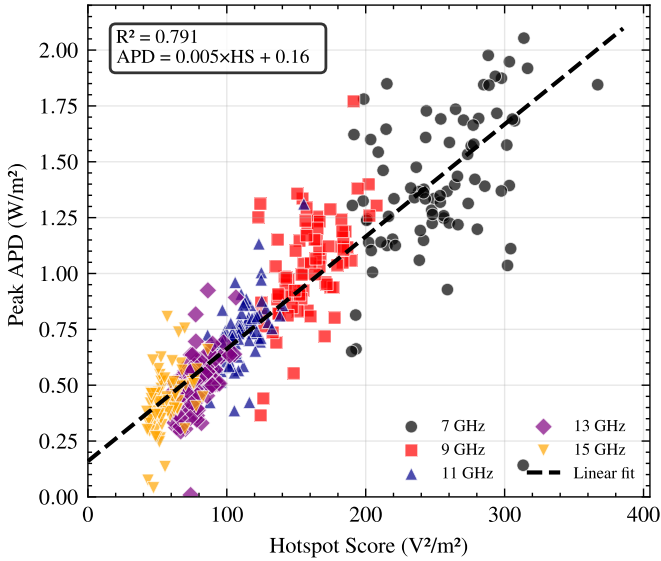


Figure 2.10: Hot-spot score predicts actual APD ($R^2 = 0.79$). Points colored by frequency: 7 GHz candidates (black) cluster at high hot-spot score and high APD. 15 GHz candidates (orange) cluster at low values.

The frequency-dependent clustering is evident: 7 GHz candidates (black) occupy the upper-right region with high hot-spot scores (200–350 V²/m²) and high APD (1.5–2.0 W/m²). 15 GHz candidates (orange) occupy the lower-left region. The relation across these configurations supports the hot-spot score as a screening proxy. The search may miss higher APD values for a particular phantom and frequency.

2.3.5 Comparison with literature

Studies in the literature report the worst single plane-wave configuration. Table 2.5 gives the average over the 12 configurations, which is 1.5–1.6 times lower. We therefore compare with the per-configuration values, listed in Table 2.8.

Bakker *et al.* [9] simulate the same four phantoms and the same 12 plane-wave configurations. They report 145% (Thelonious) and 121% (Eartha) of the basic restriction, against 145% and 122% in this work. The four worst-case whole-body SAR values differ by at most 2%. Uusitupa *et al.* [8] simulate three of the same phantoms and report 154% for Thelonious. The three values differ by at most 12%. Kühn *et al.* [10] find the 6-year-old phantom above the restriction at 100 MHz and above 1450 MHz. The worst configuration in this work first exceeds it at 1450 MHz. All of these differences are within the expanded uncertainty of $\pm 12\%$ ($k = 2$).

Dimbylow [7] simulates NORMAN, a different phantom. Its mass is 73 kg,

Table 2.8: Comparison with whole-body SAR from the literature: Bakker *et al.* [9], Uusitupa *et al.* [8], Dimbylow [7], and the closed-form model of Kodera *et al.* [19]. All values are SAR_{wb} in mW/kg for a single plane-wave configuration at 1 W/m² incident. Ratio is this work divided by the literature value.

Phantom	Maximum near 2 GHz over the tested cases						Duke, front ^c				Thelonious, side ^d			
	Bakker (2010) ^a			Uusitupa (2010) ^b			Dimbylow (2002)				Kodera (2024)			
	Theirs	Ours	Ratio	Theirs	Ours	Ratio	MHz	Theirs	Ours	Ratio	GHz	Theirs	Ours	Ratio
Duke	6.24	6.21	1.00	6.16	5.77	0.94	400 (450)	6.29	6.34	1.01	7	3.29	3.96	1.20
Ella	6.76	6.60	0.98	7.53	6.60	0.88	900 (835)	6.40	6.45	1.01	11	3.34	3.88	1.16
Eartha	9.68	9.76	1.01	—	—	—	1400 (1450)	6.33	6.11	0.96	15	3.40	3.85	1.13
Thelonious	11.60	11.61	1.00	12.32	11.61	0.94	2450	4.75	5.48	1.15	26	3.61	3.57	0.99
							3000 (3500)	3.99	4.55	1.14				

^aEartha and Thelonious from their text, Duke and Ella from their figure 4 with the corrigendum applied.

^bSampled at 2100 MHz, at the polarization they report: vertical for Duke and Thelonious, horizontal for Ella. Our value is the maximum over our directions at the same polarization. Their VF Male, VF Female and VF Boy are the same subjects as Duke, Ella and Thelonious. They do not include Eartha. ^cNORMAN, 73 kg against 72.6 kg for Duke. Our frequency in parentheses where it differs.

^dClosed-form model $\text{ACS}_{\text{wb}} \approx A_p T$, with $A_p = 0.132 \text{ m}^2$ the lateral projected area of Thelonious and T the Fresnel power transmission coefficient of skin.

against 72.6 kg for Duke. The agreement is within 4% up to 1450 MHz. Above 2450 MHz Duke absorbs 14–15% more. NORMAN is a 2.077 mm voxel model, under 7 cells per wavelength in muscle at 3 GHz. Coarse voxels under-resolve the body surface, where absorption is concentrated at these frequencies.

No whole-body SAR for a child phantom has been reported above 6 GHz. For FR3 and FR2 we therefore compare against the closed-form model of Kodera *et al.* [19]. Above 10 GHz the absorption cross section of equation (2.7) converges to $\text{ACS}_{\text{wb}} \approx A_p T$ to within 5%. Here A_p is the projected area of the body seen from the direction of incidence, and T is the Fresnel power transmission coefficient at the skin surface. For Thelonious under side illumination $A_p = 0.132 \text{ m}^2$. The model gives 3.61 mW/kg at 26 GHz, against 3.57 mW/kg in this work. The excess over the model falls monotonically from 20% at 7 GHz to 1% at 26 GHz, as expected in the geometric-optics limit. The model omits diffraction into the shadow region. This contribution decreases as the body becomes electrically larger.

2.4 Conclusion

In this chapter, we characterized RF–EMF exposure from 450 MHz to 26 GHz using 550 FDTD simulations across four phantoms, two exposure scenarios, and 15 frequencies. Environmental whole-body SAR exceeds the basic restriction for both child phantoms near 2140 MHz, in four of the twelve plane-wave configurations. The adult phantoms stay below the restriction in every configuration. Under beamforming, local $\text{psSAR}_{10\text{g}}$ at the reference level reaches 131–158% of the head/torso basic restriction at 3500 MHz. At 7 GHz, Thelonious reaches 103% of the APD basic restriction. At 700 MHz, beamforming doubles $\text{psSAR}_{10\text{g}}$ with

all phantoms remaining within limits. SAR_{wb} remains unchanged because coherent focusing redistributes absorption spatially without increasing the total absorbed power. At 15 GHz, compliance margins widen to 25–40% of the basic restriction. Beamforming causes 10 g $\text{psSAR}_{10\text{g}}$ and 4 cm^2 APD to exceed their limits at 3500 MHz and 7 GHz, respectively, at reference-level incident power. The 7 GHz excess is within the $\pm 12\%$ expanded modelling uncertainty.

Measured 5G exposure is nevertheless three to four orders of magnitude below the reference level [41].

Children show 1.5–1.9 times as high whole-body SAR as adults at all sub-6 GHz frequencies. Their higher ratio of absorption cross section to body mass (Eq. (2.7)) explains this difference. The tightest FR1 margin occurs for Thelonious at 2140 MHz. The maximum whole-body SAR over the tested configurations agrees with the literature within 2% for the same four phantoms, and with a closed-form absorption-cross-section model within 1% at 26 GHz.

Penetration depth determines tissue-specific absorption. Lower frequencies lead to higher absorption in deep tissues. Brain SAR decreases 96% from 450 MHz to 5.8 GHz. Skin SAR increases 3.2-fold as δ_{90} drops from ~ 60 mm to ~ 10 mm. Skin and brain SAR correlate negatively ($r = -0.45$, $p < 0.001$) because superficial absorption shields deep tissues such as the brain.

The main limitations are the use of four phantoms, the restriction of the 26 GHz analysis to one phantom and one incidence direction, the use of four-direction rather than environment-specific beamforming, and the restriction to a standing posture.

The organ-specific SAR data for brain, eyes, skin, and genitals support epidemiological exposure assessment across 15 frequencies.

Together, these results establish a full-wave reference for environmental and beam-focused exposure from 450 MHz to 26 GHz. The simulations resolve anatomical absorption but require a new calculation for every incident field. In Chapter 3, we will build on the results of Chapter 2 and couple the full-wave exposure model to site-specific ray-traced channels, replacing canonical incident fields with realistic indoor massive-MIMO propagation.

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3

Hybrid Ray-Tracing/FDTD Exposure Assessment

“What has been hitherto done, however, has by no means exhausted the field of electrical research.”

— James Clerk Maxwell

This chapter is adapted from:

- Robin Wydaeghe, Sergei Shikhantsov, Emmeric Tanghe, Günter Vermeeren, Luc Martens, Piet Demeester, and Wout Joseph, “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.

In Chapter 2, full-wave simulations quantified environmental and auto-induced exposure for canonical incident fields. In this chapter, we extend this dosimetry to site-specific indoor wireless channels. We combine deterministic ray tracing at room scale with finite-difference time-domain simulations near the human body at 3.5 and 28 GHz. The hybrid method uses complex path coefficients and a discrete grid of arrival directions.

3.1 Introduction

Industrial wireless systems require reliable low-latency connections with high throughput [1]. Massive multiple-input multiple-output (MaMIMO) uses precoding

across many transmit antennas to exploit the spatial diversity of the wireless channel [2, 3]. Distributing those antennas over an electrically large area can improve channel orthogonality and support cell-free networks [4, 5]. Higher-frequency bands have more bandwidth, but path loss and blockage restrict coverage. Distributed antennas can shorten the link distance, so distributed MaMIMO and millimeter-wave operation complement each other.

Exposure assessment of these systems spans two physical scales. The room-scale propagation environment determines which multipath components reach a user, whereas absorption is determined by fields resolved on the tissue scale. The ICNIRP guidelines limit both external reference quantities and quantities induced in the body [6]. Although worst-case calculations remain necessary for compliance, realistic assessment must combine both stages without discarding the amplitudes, phases, or directions of the multipath components.

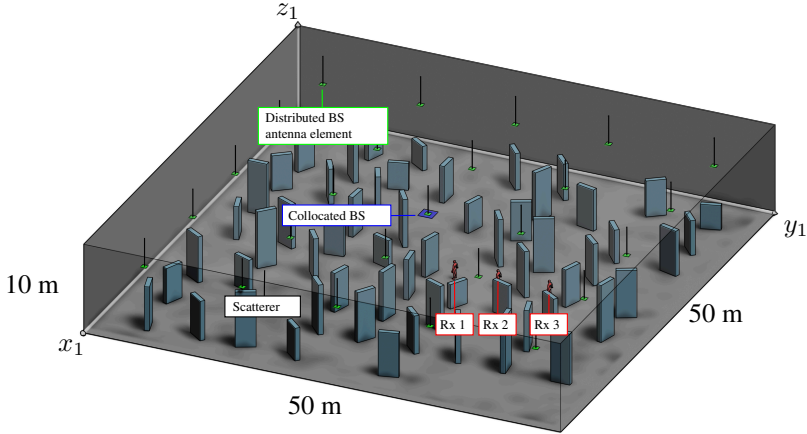
Ray tracing resolves the site-specific channel, and FDTD then determines the fields and absorption in an anatomical phantom [7]. Previous work used this hybrid method at 3.5 GHz to examine exposure hot-spots produced by distributed MaMIMO [8]. Above 6 GHz, however, the ICNIRP 2020 guidelines introduce absorbed power density as a new basic restriction, and the finer FDTD grid increases computational cost. To the best of our knowledge at the time of publication in December 2022, this was the first use of hybrid ray-tracing/FDTD to compute anatomical absorbed power density from distributed MaMIMO base stations at 28 GHz.

We apply the method to realistic base stations in two industrial environments. To the best of our knowledge, this was the first anatomical APD comparison between distributed and collocated MaMIMO at 28 GHz. We also compare the corresponding exposure results at 3.5 and 28 GHz and examine how distance and blockage affect line-of-sight and non-line-of-sight exposure.

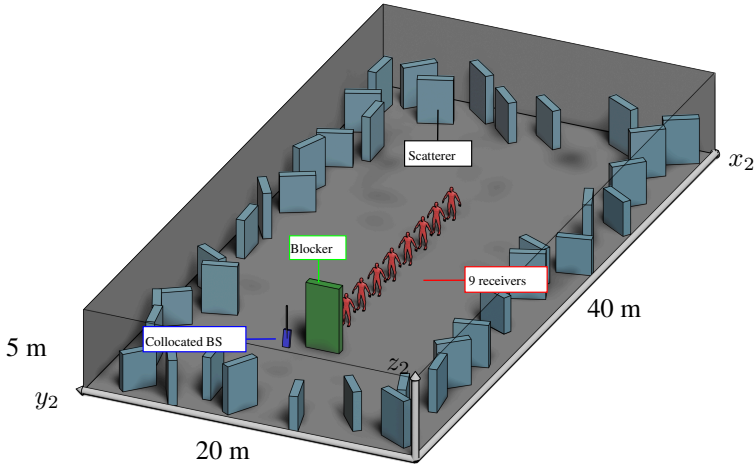
3.2 Methods

3.2.1 Configurations

Figures 3.1a and 3.1b each show a realization of the two industrial environments studied. In both, a closed concrete ($\epsilon_r = 7$, $\sigma = 1.5 \times 10^{-2} \text{ S/m}$) room containing metal cuboids models a Factory of the Future (FotF). The cuboids have fixed footprints and variable heights, as in [7], and represent metal machinery. Their position is sampled from two spatial distributions covering the room, detailed below. The scatterers reflect and diffract fields transmitted by the base-station antenna elements, reproducing the propagation diversity of an indoor industrial environment. The collocated array represents a conventional 5G base station, whereas the distributed array represents an extremely large aperture array (ELAA). The patch-antenna arrays are suspended 1 and 2 m below the ceiling in configurations 1 and 2, respectively. They emit a signal at 3.5 GHz or 28 GHz (mm-Waves). This is shown in blue in Fig. 3.1. Isotropic receiver antennas (RxS) receive this signal. The receivers



(a) The first configuration, comparing collocated with distributed MaMIMO BSs. The first BS is located at the center of the room. The second has its elements spread over the room.



(b) The second configuration, comparing LOS with NLOS exposure. The NLOS blocker shown here in green is removed for the LOS case.

Figure 3.1: The two indoor industrial environments. Each panel shows one realization with randomly placed scatterers. The red receivers mark their positions but do not scatter rays. Transparent walls and ceilings reveal the room interior.

are 1.75 m high, vertically polarized, and positioned on a straight line parallel to the room walls. They represent user equipment (UE) held beside the heads of workers moving through the FotF. Two pairs of channel types (*configurations*) are studied, namely (i) collocated and distributed MaMIMO channels and (ii) LOS and NLOS channels.

3.2.1.1 Collocated (COL) and distributed MaMIMO (DIS) channels

The room's footprint is square and has dimensions $50 \times 50 \times 10 \text{ m}^3$. We generate the scatterer distribution as in [8] by randomly removing 30% of the scatterers from a uniform grid.

Three UEs receive a signal. The number of Rx's is chosen low to reduce computational costs. The number of channel realizations is chosen high (100) to enable a statistical analysis of the exposure distributions. The first UE is placed at a horizontal separation from the BS (henceforth UE separation) of 2.5 m. The second and third have a UE separation of 7.5 and 12.5 m.

3.2.1.2 Line-of-sight (LOS) and non-line-of-sight (NLOS) channels

The room's footprint is rectangular with dimensions $40 \times 20 \times 5 \text{ m}^3$. The distribution of the scatterers is as in [7], i.e., using the Poisson Disk sampling algorithm. Results are given with and without a $2 \times 0.5 \times 5 \text{ m}^3$ blocker. Nine UEs receive a signal to enable an analysis as function of receiver position. The first and last receivers have UE separations of 6 and 22 m, respectively. We use five channel realizations to limit computational cost.

3.2.1.3 Parameters

The numerical pipeline uses the n77 and n261 bands, hereafter called the 3.5 and 28 GHz bands, respectively. Their spectrum parameters are listed in Table 3.1. Two realistic BSs are modeled for 5G coverage at these frequencies. In configuration 2, their dimensions and element arrangements are estimated from the named commercial devices. Their physical parameters are listed in Table 3.3.

Table 3.1: Spectrum parameters of the 3.5 and 28 GHz bands used in the simulations.

	3.5 GHz band	28 GHz band
Frequency band	n77	n261
Central frequency [GHz]	3.75	27.9
Wavelength [mm]	79.9	10.7

The parameters used for the RT simulations are shown in Table 3.2. These parameters are sufficient to accurately simulate the channel in the modeled indoor environment [9]. The MaMIMO BS is an array consisting of equally spaced dual-polarized antenna elements. Their parameters are also listed in Table 3.3. The collocated array has an inter-element spacing of 0.5λ in both the vertical and

horizontal directions. In the distributed case, the inter-element spacing is 10 m, such that it covers the whole room.

Table 3.2: Computational parameters of the ray-tracing simulations for both configurations and both frequency bands.

	Configuration 1: COL/DIS		Configuration 2: LOS/NLOS	
	3.5 GHz band	28 GHz band	3.5 GHz band	28 GHz band
Reflections	5	5	6	5
Transmissions	0	0	2	2
Diffractions	1	1	2	1
Threshold [dBm]	-250			
Angular spacing [°]	0.25			
Collection radius [cm]	31.5		20.0	

Table 3.3: Physical parameters of the realistic BSs for both configurations and both frequency bands. The Ericsson base stations' parameters are not public, so the listed values are estimates based partly on device dimensions.

Configuration 1: collocated/distributed MaMIMO		
	3.5 GHz band	28 GHz band
Base station model name	N/A	N/A
Total EIRP power ^a [dBm]	55	55
Antenna configuration ^b	1 × 5 × 5	1 × 5 × 5
Inter-element spacing	COL: 0.5λ × 0.5λ; DIS: 10 × 10 m	
Antenna element type	Patch antenna (ε _r = 4.4)	
Element dimensions [mm]	3 × 3 × 1.5	3 × 3 × 1.5
Maximum gain ^c [dBi]	4.79	7.35
Tilt	90° (facing the floor)	
Configuration 2: line-of-sight/non-line-of-sight		
	3.5 GHz band	28 GHz band
Base station model name	Ericsson AIR 6449	Ericsson StreetMacro 6701
Total EIRP power ^a [dBm]	55	55
Antenna configuration ^b	2 × 8 × 12	2 × 8 × 8
Inter-element spacing [λ]	0.89 × 0.71	6.8 × 2.7
Antenna element type	Dipole (PEC)	Dipole (PEC)
Element dimensions [mm]	79.9 × 0 × 0	10.7 × 0 × 0
Maximum gain ^c [dBi]	2.15	2.15
Tilt	10° (facing the receiver)	

^aThe total EIRP is divided equally among the antenna elements. ^bThe first dimension is the number of polarizations; two denotes the bowtie formation. ^cMaximum gain is normal to the antenna-element array plane.

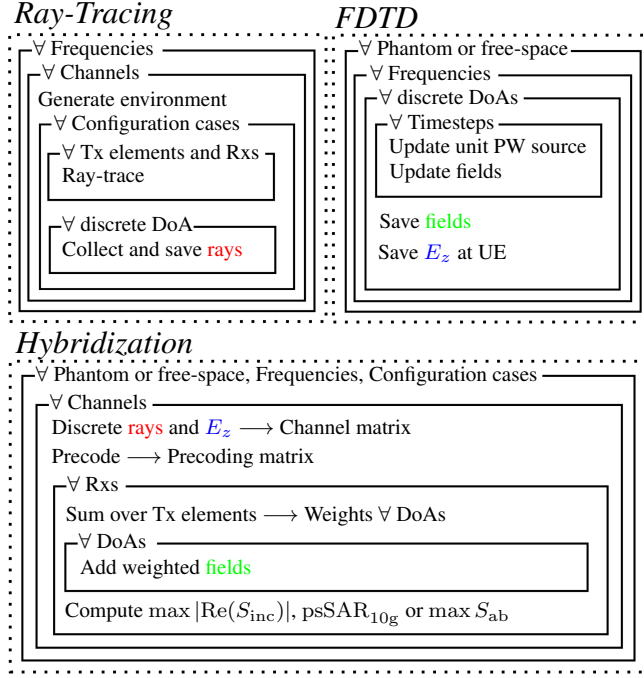


Figure 3.2: Flowchart of the numerical pipeline for one configuration. Independent RT and FDTD initialization precedes the hybridization step, which combines the colored data into exposure quantities. Each labeled box repeats over the dimension marked by $\forall$.

3.2.2 RT-FDTD

The hybrid RT-FDTD tool developed in [7] is extended to mm-Wave frequencies. The fundamental method is the same: the scattered EMFs by plane waves (PWs) are first stored and then combined based on the full channel matrix.

Following Shikhantsov *et al.* [7], we write this linear combination as

$$\mathbf{E}(\mathbf{r}) = \sum_q a_q \mathbf{E}_q^{\text{FDTD}}(\mathbf{r}). \quad (3.1)$$

The index q denotes a plane-wave excitation in the precomputed library. The corresponding field response $\mathbf{E}_q^{\text{FDTD}}$ includes scattering and penetration in the head. The complex weight a_q contains the ray amplitudes and precoding weights assigned to that excitation. Adding these fields keeps their relative phases. The schematic specifies how this fundamental method is looped over all parameters of interest, for one configuration. The RT and FDTD initialization followed by their hybridization are detailed schematically in Fig. 3.2.

We adapt the FDTD initialization and exposure evaluation to 28 GHz, as shown in Fig. 3.3. A Multimodal Imaging-Based Detailed Anatomical Model of the

Human Head and Neck (MIDA) [10] is used as a phantom. The phantom is highly detailed and features a spatial isotropic resolution of $500\text{ }\mu\text{m}$ [11], shown in the upper front head. The model is finely voxelized due the small wavelength used, shown in the lower head. The head faces the BS, i.e., in the positive y_1 -direction or negative x_2 -direction for configuration 1 and 2, respectively. Maximum ratio transmission (MRT) precoding is used in a single-user down-link (DL) transmission scenario. The incoming rays focus the z -component of the electric field to the location of a vertical dipole, representing the UE. Vertical and horizontal slices show stronger fields around the focus point in yellow and white. This *hot-spot* is a result of focused rays interfering constructively. The focus point is located 2 cm behind the right ear, within the bounding box of the phantom. This ear-adjacent focus represents a UE held beside the head. Prior work often found peak exposure in ear skin [8]. The surface absorbed power density S_{ab} averaged over a 4 cm^2 surface is shown on the back of the head. Red indicates higher S_{ab} near the hot-spot.

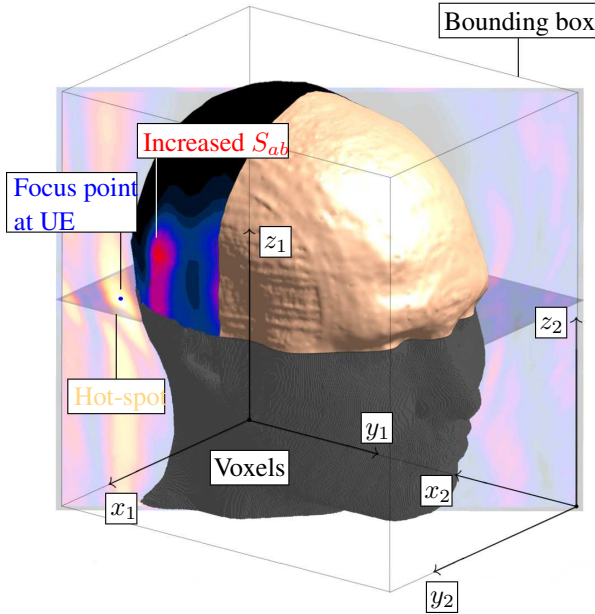


Figure 3.3: The FDTD-domain. A hot-spot is shown in yellow around the focus point in blue. Increased surface absorbed power density S_{ab} is shown in red on the skin. The phantom including the skin, shown in beige, is voxelized at 28 GHz, shown in gray.

3.2.3 Computational considerations

The MaMIMO BS requires the knowledge of the wireless channel to perform the precoding. We calculate the channel matrix coefficient as the sum of the signals

with different directions of arrival (DoAs) [12]. A signal is the electric field's z -component received at the location of the UE. The field is computed with an FDTD simulation of a unit PW incident on the human head phantom.

We represent the incident field over the head domain by plane waves. The local FDTD model includes tissue scattering and penetration. We neglect fields scattered by the head and subsequently reflected back by the room.

The higher frequency results in prohibitively large computational costs (due to, e.g., the Courant limit [13]). Therefore, the execution time of each FDTD simulation at 28 GHz is reduced by a combination of techniques. First, the workflow of Fig. 3.2, including pre- and post-processing, is parallelized on a high-performance computing cluster with 40 CPUs and a high-performance GPU. Second, the ray approximation is more accurate at higher frequencies, so the RT simulations require fewer rays. As a result, the number of reflections and diffractions is decreased, as shown in Table 3.2. At 27.9 GHz, the voxel size is 0.72 mm, approximately $\lambda_0/15$ for the free-space wavelength $\lambda_0 = 10.75$ mm. At 3.75 GHz, the voxel size is 1.75 mm, approximately $\lambda_0/46$. The numbers of voxels at 3.5 and 28 GHz are 1.54 and 22.12 million, respectively. However, the computing and memory costs remain high. The larger field-data volume limits the numbers of DoAs, channel realizations, and UE separations because every case requires data export, summation, and weighting.

The 0.72 mm mesh at 27.9 GHz is finer than $\lambda_0/10$. To limit storage and processing costs, the number of DoAs is set to 20, which still enables the modeling of hot-spots. The error is estimated in [7]. We group the incident multipath components into these directions and add their fields coherently. The number of geometric paths reaching the receiver can be larger.

In configuration 1, the number of channel realizations is chosen large (100). Therefore, we study the exposure distributions in this configuration. In configuration 2, the number of receivers is chosen large (9). Thus, we study the influence of position in this configuration.

3.2.4 Exposure assessment

At both 3.5 and 28 GHz, the ICNIRP reference quantity is the incident power density S_{inc} in free space. Here, a free-space computational domain is simulated without phantom. The MIDA phantom is added when simulating for the basic restrictions. The basic restriction at 3.5 GHz is given by the peak-spatial specific absorption rate averaged over a 10-g cube (psSAR_{10g} in W/kg) [6, 14]. At 28 GHz, the maximum surface absorbed power density S_{ab} (in W m⁻²) averaged over a 4 cm² surface is used to better account for the superficial nature of the exposure [6, 15]. We define η as the percentage ratio between each simulated exposure quantity γ ($|\text{Re}S_{\text{inc}}|$, psSAR_{10g} or S_{ab}) and its maximum allowed value for the general public (GP) γ_{limit} , as set by the ICNIRP guidelines:

$$\eta_\gamma = \frac{\gamma}{\gamma_{\text{limit}}} \cdot 100\%. \quad (3.2)$$

The values of γ_{limit} are listed in Table 3.4. All exposure quantities are local to the head and time averaged. The basic quantities should remain below their respective limits. Dividing the basic-quantity percentage η_b by the reference-quantity percentage η_r is equivalent to setting the reference quantity to its limit. This results in the definition of α ,

$$\alpha = \frac{\eta_b}{\eta_r} \cdot 100\%, \quad (3.3)$$

where η_b is the percentage of the applicable basic restriction reached by the basic quantity. A value of α above 100% means that the basic restrictions would be exceeded if incident power densities are set to the reference levels. This is called hot-spot normalization [16].

Table 3.4: The exposure quantities γ and their limiting values in both frequency bands according to the ICNIRP 2020 guidelines for the general public. The quantities are averaged over space and time as defined in the text.

$\gamma \leq \gamma_{\text{limit}}$	3.5 GHz band	28 GHz band
Reference level	$ \text{Re } S_{\text{inc}} \leq 10 \text{ W/m}^2$	$ \text{Re } S_{\text{inc}} \leq 10 \text{ W/m}^2$
Basic restriction	$\text{psSAR}_{10g} \leq 2 \text{ W/kg}$	$S_{\text{ab}} \leq 20 \text{ W/m}^2$

3.3 Results

3.3.1 General results

In Figures 3.4 through 3.7, results from the first configuration (COL/DIS) are presented in a matrix of plots, comparing across frequency (the 3.5 and 28 GHz frequency bands) and BS type (the collocated and distributed MaMIMO BSs). The main interest is how the exposure values are distributed for each of these cases. The vertical axes show the cumulative distribution functions (CDFs) of the exposure quantity from the 100 channel realizations. The bottom horizontal axes of the plots are the normalized exposure quantities. The top horizontal axes are scaled such that they display the corresponding η value for the actual output power of 320 W (55 dBm). Three colored lines are associated with each Rx shown in Fig. 3.1a. The “All rx” line combines all 300 channel realizations into one CDF. A vertical line marks the 95th percentile.

In Fig. 3.8 and 3.9, results from the second configuration compare the 3.5 and 28 GHz bands side by side. The main interest is how the exposure values depend on position to the BS and presence of a blocker. The left and right vertical axes show the exposure quantity and its corresponding η value, respectively, at 320 W base-station output power. The horizontal axis shows UE separation. Two lines are associated with the absence (LOS) or presence (NLOS, shown in Fig. 3.1b) of the blocker. Each result is represented by a dot. The number of channel realizations is 5, which estimates the mean and standard deviation of the exposure in LOS or NLOS. Lines connect the average of the 5 channel realizations across UE separation.

3.3.2 Configuration 1: COL vs DIS

In general, the Rxs closest to the BS have the highest exposure, in particular for the first Rx. However, the focus of this configuration's analysis is not on position, but on the distributions of exposure quantities. One hundred channel realizations were necessary to sufficiently resolve the exposure distributions.

3.3.2.1 Reference quantities

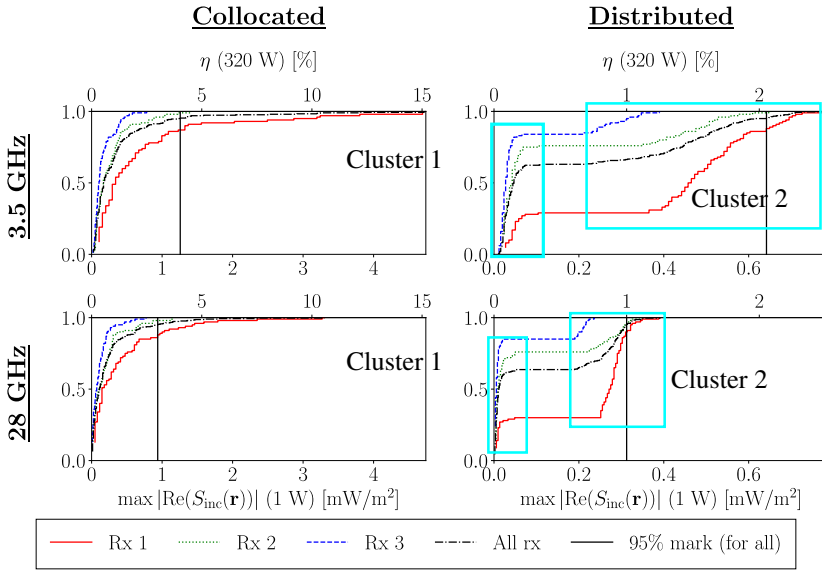


Figure 3.4: Reference quantities normalized for a 1 W radiating BS in configuration 1. Section 3.3.1 defines the axes and normalization. In the distributed MaMIMO case, the cyan line at 0.19 mW/m^2 separates two exposure clusters.

The results of the reference quantities are shown in Figure 3.4. Realistic values are at most 4% of their limits in 95% of cases for a BS radiating 320 W. All exposure metrics are smaller by a factor of 2–3 with a distributed BS than with a collocated BS. For the distributed BS, more elements are distant from the receivers, reducing the total incoming power. The collocated exposure CDFs have a shape consistent with a Ricean model. This suggests that a LOS component or strong reflection path dominates the channel. The distributed reference-exposure CDFs show low- and high-exposure clusters separated around 0.19 mW m^{-2} . Approximately 29–30%, 76% and 84–85% of the plotted values lie below this split for Rx 1, Rx 2 and Rx 3, respectively, across the two frequency bands. We use “clusters” descriptively for these ranges in the plotted distributions. In the first cluster, a similar exposure distribution to the collocated BS is seen. The standard deviation of the second

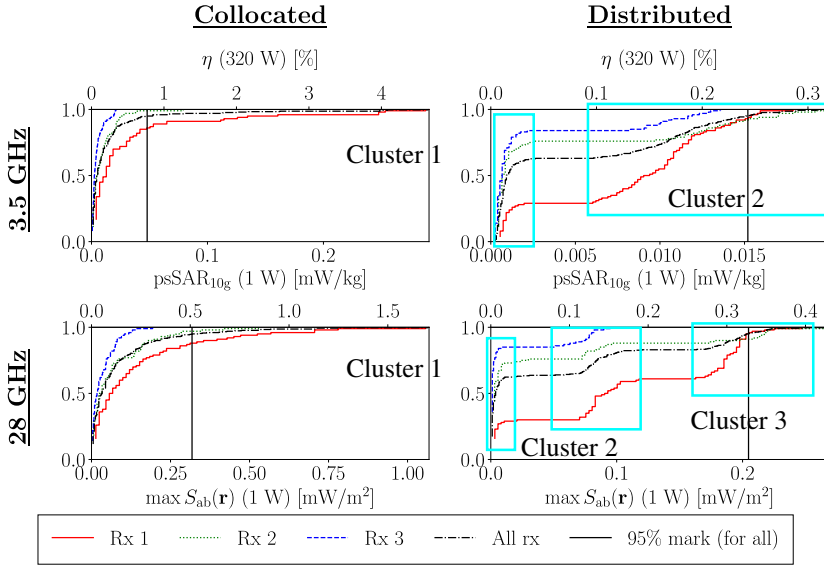


Figure 3.5: Basic quantities normalized for a 1 W radiating BS in configuration 1. Clarification of this figure is provided in Section 3.3.1. In the distributed MaMIMO case, exposure clusters can be seen, shown in cyan on the horizontal axis. For 28 GHz, three are seen, delimited around 0.05 mW/m^2 and 0.15 mW/m^2 .

cluster is 4.5 times broader than the first. One possible explanation is the following. When a UE is surrounded by scatterers, the probability that exposure belongs to the first cluster is highest. The channel resembles that of the collocated BS, because the interaction happens mainly by one or a few nearby antenna elements. When no nearby scatterers shadow the UE, the probability that exposure belongs to the second cluster is highest. The interaction can now occur with a larger number of antenna elements farther from the UE. Therefore, the rays may undergo more reflections and diffractions. The variability in exposure is thus higher. As seen in Fig. 3.1a, the scatterers belong to a regular grid, the antenna elements are directly above this grid, and the receivers are located at the center of each grid cell. This set-up makes it possible for receivers to be completely encircled or not by scatterers. Similar exposure distributions are observed when comparing the 3.5 and 28 GHz bands. With the collocated BS, the 95th percentile is 12% lower at mm-Wave frequencies. With the distributed BS, the reduction is 55%. In this case, the standard deviation of the second exposure cluster is much lower. This is likely due to the increased path loss at these frequencies reducing the number of interactions with distant antenna elements.

3.3.2.2 Basic quantities

The results of the basic quantities are shown in Fig. 3.5. Realistic values are at most 0.85% of their limits in 95% of cases. These η values are generally 5–10 dB below those of the reference quantities. As a result, the α value is less than one and the basic quantities stay 5 to 10 dB below their limits when the reference quantities are set to their limits. The same conclusions as above can be drawn about the values and exposure distributions. The incoming electric fields are identical because the propagation of the rays onto the phantom is the same (the *propagation step*). Differences between Fig. 3.4 and 3.5 can only be attributed to the exposure metric used and the presence of the phantom (the *exposure step*, shown in Fig. 3.3). The similar distributions indicate that variation in received power explains much of the variation in these exposure metrics for these channels. Absorption still depends on the angular, phase and polarization structure of the incident field, as seen for the distributed 28 GHz case. However, in the 28 GHz band with the distributed BS, three exposure clusters are seen, delimited around 0.05 mW m^{-2} and 0.15 mW m^{-2} . This deviation can only be explained by the interplay of the propagation and exposure step. Because high exposure clusters are more prominent in NLOS propagation, the formation of hot-spots is more likely in the high exposure clusters. When the location of the hot-spot is within a certain distance of the skin, the hot-spot causes increased exposure. Only the superficial S_{ab} metric on the phantom skin registers this increase. The aforementioned α value is highest in this case because of this effect.

3.3.2.3 Normalized results to incoming Rx power

Before the precoding step, the total power is split evenly among the antenna elements. In the distributed MaMIMO BS case, the receiver is surrounded by a small number of antenna elements each having a fraction of the total output power. In the collocated MaMIMO BS case, the receiver is near all antenna elements radiating the total output power. The exposure quantities are therefore substantially lower with distributed BSs compared to collocated ones. Neither commercial distributed MaMIMO BSs nor corresponding regulations yet exist. The realistic total output power of such systems is therefore unknown. The output power is presumably higher, and likely dependent on the number of antenna elements and the area covered. Therefore, the above conclusion may not be realistic due to the equal power assumption. There are a number of ways to *normalize* the exposure quantities such that a fair comparison becomes possible. One of them is dividing the result by the total incoming power P^{Rx} on the Rx. The total electric field is

$$E^{\text{tot}} = \sum_i w_i \hat{E}_i,$$

where i denotes a DoA angle, w_i is the corresponding weight from the precoding matrix and $\hat{E}_i$ is the electric field for a unit PW with DoA angle i . The total

incoming power is defined as

$$P^{\text{Rx}} = \sum_i |w_i|^2.$$

The results are now normalized w.r.t. both 1 W total power from the Tx and 1 W incoming power on the Rx. The simulated exposure value γ is retrieved as follows:

$$\gamma = P_{\text{BS}} \cdot P^{\text{Rx}} \gamma_1^{\frac{1}{\text{W}}}.$$

In this equation, P_{BS} is the BS's total emitted power and $\gamma_1^{\frac{1}{\text{W}}}$ is the doubly normalized exposure quantity. The latter is shown in Figures 3.6 and 3.7 for the reference and basic quantities, respectively. After normalization by the total incident coefficient power, the reference-exposure CDFs overlap more closely and the broad low- and high-exposure separation is no longer apparent. The distributed 28 GHz absorbed-power CDFs still differ across receivers. Local field focusing and skin coupling may contribute to these differences. Approximately 55%, 82% and 99% of the plotted values lie below $5 \mu\text{W m}^{-2}$ for Rx 1, Rx 2 and Rx 3, respectively. We use “clusters” descriptively for the ranges visible in these simulated distributions.

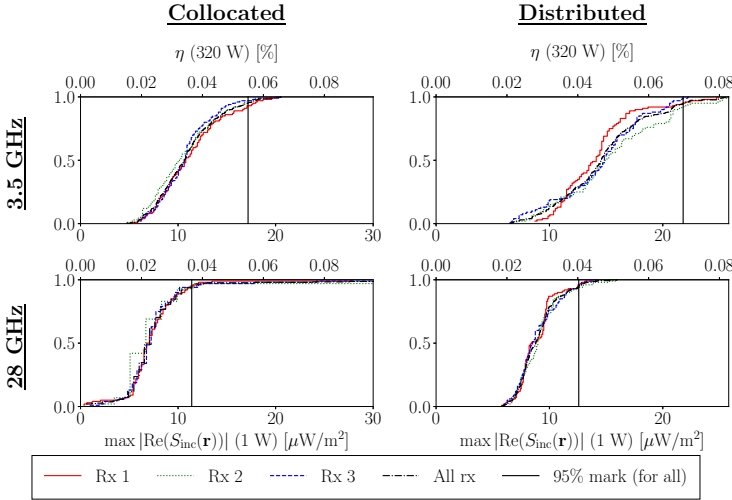


Figure 3.6: Reference quantities normalized for a 1 W radiating BS and for 1 W total incident power on the Rx in configuration 1. Clarification of this figure is provided in Section 3.3.1. No clusters are observed.

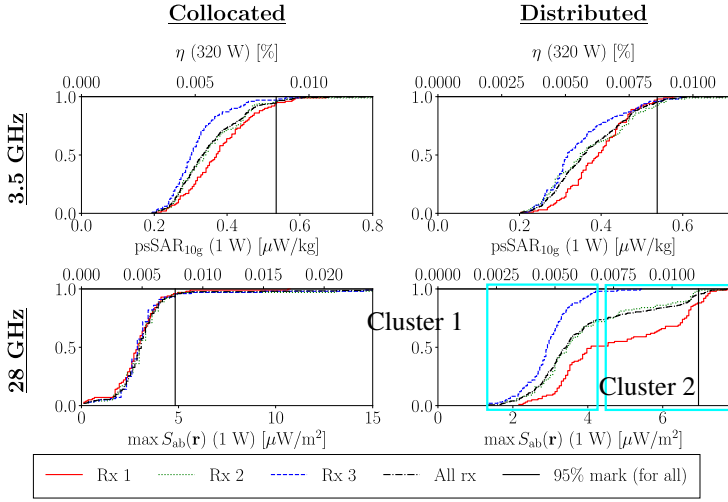


Figure 3.7: Basic quantities normalized for a 1 W radiating BS and for 1 W total incident power on the Rx in configuration 1. Clarification of this figure is provided in Section 3.3.1. Clusters, shown in cyan on the horizontal axis, are only observed in the distributed MaMIMO 28 GHz case, delimited around $5 \mu\text{W m}^{-2}$.

3.3.3 Configuration 2: LOS vs NLOS

Figures 3.8a and 3.8b compare the reference quantities as a function of distance at 3.5 and 28 GHz, respectively. Figure 3.9 does so for the basic quantities. All distance profiles are highly correlated across frequency and exposure quantity. The maximum η values in LOS are highest for the reference quantities. They are lowest for the basic quantities in the 28 GHz band. Therefore we find again that the α values are lower than 1. The results for the 3.5 GHz band are similar to those found in [16]. Differences are attributed to the different configurations used. For the simulated head-exposure configurations, the basic quantities remain below their limits after normalization to the reference quantity's limit. When comparing the LOS case with the NLOS case, expected results are obtained. First, the LOS exposure quantities decrease according to a power law. The NLOS exposure quantities do not. Second, the standard deviation is lower for LOS than in the NLOS case. Both of these can be explained by the free-space LOS rays dominating the channel. The results' dependence on the environment is then lower for LOS than in the NLOS case. Under NLOS conditions, exposure peaks at UE separations of 12–17 m because the blocker is located 5 m from the base station. This distance sweep gives the exposure along a route through the room, with the transmitter position, array and receiver orientation held fixed.

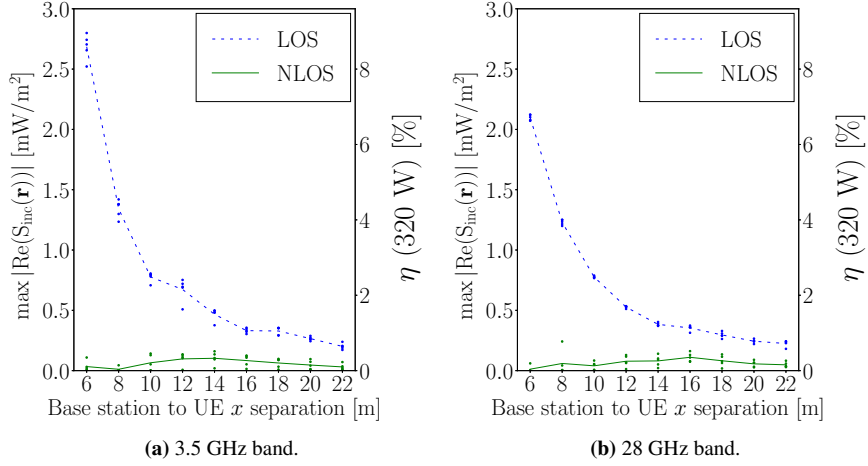


Figure 3.8: Reference quantities for a 1 W radiating base station in configuration 2. Section 3.3.1 defines the axes and normalization. Exposure is closer to the applicable limit at 3.5 GHz than at 28 GHz.

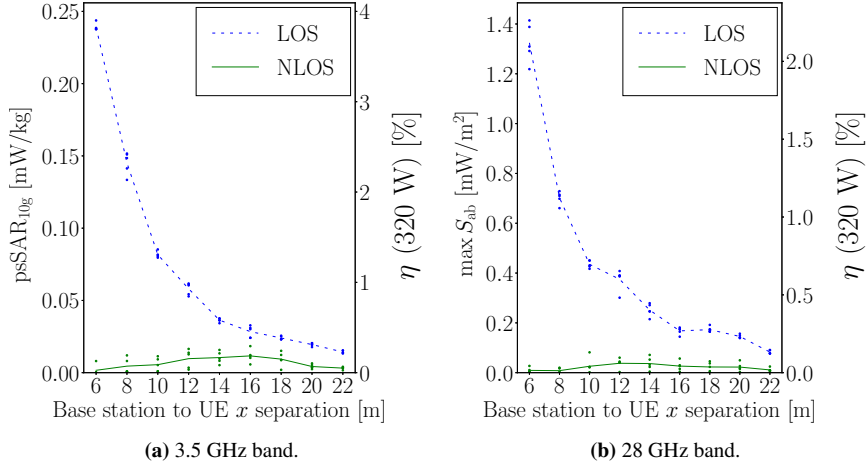


Figure 3.9: Basic-restriction quantities for a 1 W radiating base station in configuration 2. Section 3.3.1 defines the axes and normalization. Exposure is closer to the applicable limit at 3.5 GHz than at 28 GHz.

3.4 Conclusion

In this chapter, we extended the hybrid RT–FDTD method to 28 GHz by incorporating the absorbed power density required by the ICNIRP 2020 guidelines [6]. In the collocated/distributed comparison, the largest 95th-percentile value was 4% of the applicable limit, for collocated base stations at 3.5 GHz. For equal transmitted power, distributed base stations produced exposure metrics smaller by a factor of 2–3. Exposure was also lower at 28 GHz than at 3.5 GHz because of the greater path loss.

Zhekov and Xu [17] later compared their findings with our study in this chapter. They studied distributed and collocated arrays in an industrial indoor environment at 3.5 GHz, with single- and multi-user precoding and three power-normalization conditions. Their distributed deployments had lower 95th and 99th percentiles of incident power density, while median exposure had no consistent ordering across their scenarios.

The distributed deployments produced clusters in the exposure distributions. Normalizing by the power incident at the receiver removed most of this structure, showing that it originated primarily in the propagation stage. In the distance-and-blockage configuration, line-of-sight exposure followed a power law, whereas the non-line-of-sight blocker produced the expected shadowing. Across both configurations, basic restriction quantities were 5–10 dB lower relative to their limits than the corresponding reference quantities.

In Chapter 4, we will add stochastic channel modeling and apply the hybrid method developed in Chapter 3 to outdoor cell-free massive MIMO. Chapter 6 provides experimental validation of the incident-field predictions.

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4

Hybrid Ray-Tracing/QuaDRiGa–FDTD Exposure Assessment

“+++ Divide By Cucumber Error. Please
Reinstall Universe And Reboot. +++”

— Terry Pratchett, *Hogfather* (Hex)

This chapter is adapted from:

- Robin Wydaeghe, Sergei Shikhantsov, Günter Vermeeren, Luc Martens, Emmeric Tanghe, and Wout Joseph, “Hybrid ray-tracing-QuaDRiGa/FDTD method for realistic 28 GHz exposure with 6G CF-MaMIMO in 3D outdoor environments,” *npj Wireless Technology*, vol. 2, article 13, 2026, doi: 10.1038/s44459-026-00031-4.

In Chapter 3, we coupled deterministic indoor ray tracing to FDTD dosimetry. In this chapter, we extend the hybrid method to outdoor CF-MaMIMO. We combine site-specific geometry with stochastic small-scale variations in the channel and couple the resulting channel to FDTD. The resulting method supports exposure assessment along realistic urban routes.

4.1 Introduction

CF-MaMIMO and mmWave operation are candidate technologies for increasing the capacity of future cellular networks [1–3]. The former distributes many synchronized antennas over a wide area, whereas the latter provides wider bandwidths at

the cost of greater path loss. In DMaMIMO, elements can be distributed, e.g., on a building facade, reducing the path length to the UE [4]. CF-MaMIMO extends this principle to a very large number of synchronized access points (APs) distributed throughout a large geographical area [2, 5]. Radio stripes (RSs) are a prototype implementation of this paradigm [6]. Each MaMIMO transmitter uses phase and amplitude modulation across its elements to concentrate the emitted field toward the active UE [7]. Infrastructure for the 5G sub-6 GHz bands is widespread, and some cellular providers also deploy mmWave BSs [8].

A portion of the population is concerned that these new technologies could lead to adverse health effects, sparking deployment stops, protests, and general worry [9]. Although deployed BSs always undergo stringent safety testing, research is needed to quantify the realistic EMFs from novel antenna systems in relation to the guidelines set by the ICNIRP [10]. The 2020 ICNIRP guidelines introduced the surface-absorbed power density metric S_{ab} for frequencies above 6 GHz. Between the transmission of EMFs from the BS and the absorption in the human body, numerical dosimetry studies often focus on a specific part of the radio channel, making *worst-case* assumptions about other parts [11]. There is a gap in the current literature on *realistic* daily exposure from EMFs with comprehensive end-to-end simulations. For example, [12, 13] introduce complex workflows to increase the realism of exposure estimation, but ultimately do not relate their findings to absorption values in humans. However, these findings would interest both concerned citizens and policy-makers due to 5G and 6G's novelty, in particular as a result of MaMIMO technology. In addition, fully integrated simulations enable EMF-aware network planning. Here, the locations and powers of BSs in future networks can be realistically tuned before deployment. Finally, they enable the characterization of "hot-spots": wavelength-sized regions of increased EMF shaped by the precoding of BS transmission, the propagation environment, and the user [14–16]. Besides some general features, the detailed characteristics of hot-spots in realistic environments are not known, especially at mmWave frequencies. Therefore, we comprehensively study hot-spots in realistic environments at 28 GHz.

To model the exposure from these technologies, the *propagation step* (computing the incident fields in an environment) needs to be interfaced with the *exposure step* (computing the absorbed exposure on a human) in one integrated method. The MaMIMO BS estimates the channel between receiver (Rx) and transmitter (Tx) using pilot waves. The transmitted symbols are then precoded in a process known as beamforming. For LOS transmission scenarios, this causes (a) the direction of maximum gain to be aligned toward the Rx and (b) the individual elements' phases of the Tx to align causing constructive interference at the exact location of the UE's antenna [17]. When several beams impinge on the UE, either from multipath components or from a DMaMIMO system, a wavelength-sized region of increased EMF is formed at the location of the UE. Under MRT precoding, the signal-to-noise ratio (SNR) at Rx increases without bound as a function of the number of antenna elements and channel diversity [7]. The maximum hot-spot E-field also increases with the received signal, but the relationship is unclear. Therefore, we study the effects of these hot-spots from MaMIMO BSs on human RF-EMF exposure.

To inform the general public and policy-makers of realistic 5G EMF levels, and to enable EMF-aware network planning, integrated end-to-end methods should be able to map exposure almost anywhere in the world. Google introduced an API for their photorealistic meshes [18]. The digital twin of the world provides environments with full 3D level of detail (LoD), instead of 2D or 2.5D LoD, required for accurate mmWave radio channel modeling [19, 20]. Google textures the meshes but does not assign their faces to semantic classes such as buildings, terrain, vegetation, cars, water, and boats. These classes are needed to assign material properties for ray tracing. Advances in deep learning enable the semantic classification of these meshes to be performed with an accuracy of 93% [21].

Hybrid RT/FDTD is an example of an integrated method [22]. The method was used to study hot-spots at 3.5 GHz [14]. However, the first RT step is not appropriate to study exposure with high coverage in many different environments because RT is computationally intensive. Moreover, comprehensive data on the dielectric parameters and scattering of the materials is limited, especially at mmWave frequencies [23]. A new hybrid QuaDRiGa/FDTD method was proposed in [24] based on the state of the art (SOTA) QuaDRiGa [25]. QuaDRiGa renders the computations more efficient. However, the method is not suitable for site-specific simulations with high accuracy, as the large-scale fading (LSF) does not align deterministically with the environment [15]. The computational requirements scale with the fourth power of frequency. Hence, there is a need to rethink the hybridization and exposure steps to obtain the exposure metrics efficiently.

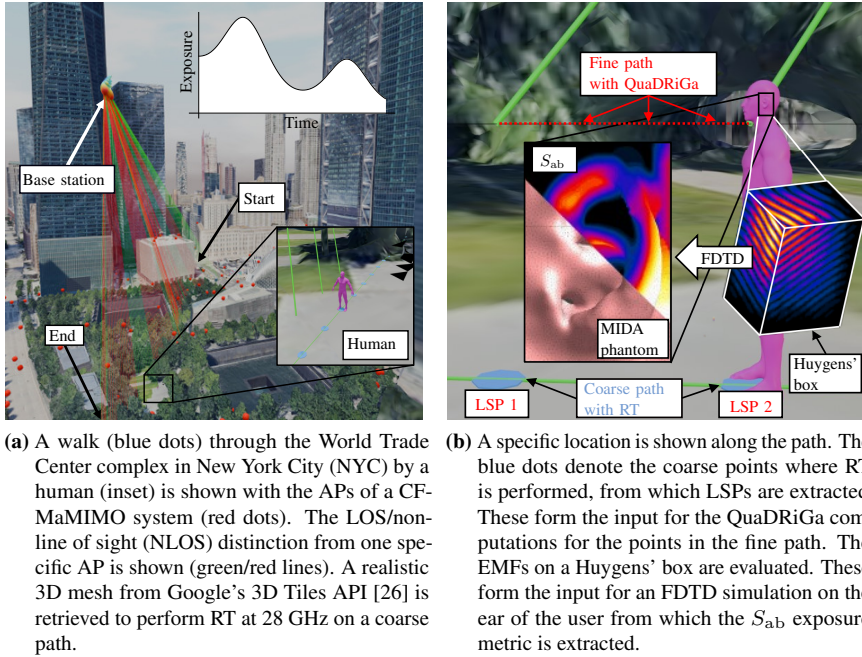
This chapter makes the following contributions:

1. The first end-to-end method for exposure assessment at mmWaves. RT and QuaDRiGa simulations are leveraged efficiently, with a Huygens' box to interface the incident EMFs to FDTD simulations.
2. The first reported application of high-accuracy, high-coverage photogrammetry in a scientific publication, in particular to compute realistic exposure along any path. For the first time, a semantic classifier is applied to these meshes.
3. Comparison of collocated and cell-free MaMIMO in both user and non-user scenarios at 28 GHz.
4. Characterization of realistic hot-spots at 28 GHz in realistic 3D environments. Their influence on the exposure metrics, the S_{inc} and new surface-absorbed power density (S_{ab}) for frequencies above 6 GHz, is examined.

4.2 Methods

The integrated end-to-end method begins with a realistic walk of a user holding a smartphone and ends with the evaluation of the exposure metrics along this walk. The method comprises four main steps. First, the configuration step defines the Rx, Tx, and environment. Second, the propagation step computes the channel at

the user's UE. Third, the hybridization step computes the EMFs impinging on the human body. Fourth, the exposure step uses FDTD and post-processing to return the exposure metric. Fig. 4.1(a) illustrates the configuration and propagation steps, and Fig. 4.1(b) illustrates the hybridization and exposure steps.



(a) A walk (blue dots) through the World Trade Center complex in New York City (NYC) by a human (inset) is shown with the APs of a CF-MaMIMO system (red dots). The LOS/non-line of sight (NLOS) distinction from one specific AP is shown (green/red lines). A realistic 3D mesh from Google's 3D Tiles API [26] is retrieved to perform RT at 28 GHz on a coarse path.

(b) A specific location is shown along the path. The blue dots denote the coarse points where RT is performed, from which LSPs are extracted. These form the input for the QuaDRiGa computations for the points in the fine path. The EMFs on a Huygens' box are evaluated. These form the input for an FDTD simulation on the ear of the user from which the S_{ab} exposure metric is extracted.

Figure 4.1: Illustration of the (a) configuration and propagation steps, and the (b) hybridization and exposure steps.

4.2.1 Configuration step

A flowchart of the configuration step is detailed in Fig. 4.2. The only input is the start and destination addresses that a pedestrian traverses. This outputs a 2D path and region around it. The 2D path is processed to a sampled set of 3D points along the path in the environment that are omnidirectional antennas, representing the Rx. The region defines the environment, which is processed for use in RT simulations. The region also defines the locations of MIMO BSs, either collocated when studying 5G or cell-free when studying 6G.

Processed and classified environments: High-accuracy environments are essential for accurate ray-tracing simulations. In particular for mmWave frequencies, it is not sufficient to model building facades as flat surfaces [20] or street canyons without cars or lampposts [27]. Foliage is rarely modeled with individual trees. The wavelength at 28 GHz is 10.7 mm. Therefore, centimeter-sized features significantly affect the multipath diversity of the channel. A greater number of NLOS

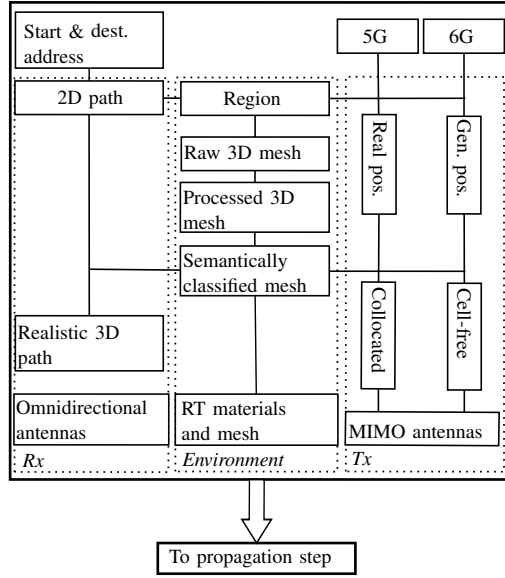


Figure 4.2: Flowchart of the configuration step.

paths can be utilized to beamform the signal toward the UE. The API for photo-realistic 3D tiles [18] is applicable to any location 3D-mapped by Google Earth. The reference in [28] provides the first examination of its accuracy compared to established methods. The mesh includes vehicles, street furniture, individual trees and building facade details, significantly improving the realism of the channel with clutter.

The input for the entire pipeline follows from the origin and destination of the user's path. First, the quality of the mesh returned from the API is improved. Then, the mesh is split into 6 classes using a deep learning model [21]. Finally, the mesh is further simplified to be suitable for ray-tracing, and each class is assigned one suitable material.

The quality-improvement step streams the highest available LoD with a Blender renderer [29]. A 100 m margin is retained around the user path, the thin mesh is solidified by 50 cm, the volume is voxelized at 20 cm resolution, and the original texture is rebaked onto the new mesh. These operations remove common photogrammetry artifacts and reduce the mesh size. The semantic classifier was trained on a 4 km² area in central Helsinki and achieved an overall object-label accuracy of 93% in the SUM evaluation. The accuracy may differ in New York, and material assignments may introduce further errors. The Helsinki and NYC cases apply the classifier in environments with different levels of urbanization. In the final simplification step, polygons whose normal vectors differ by less than 5° are merged. The simplification preserves small features such as trees while reducing polygons on nearly planar features such as water.

Receiver path: The channel and exposure are computed along a path a user takes. The user's path is composed of a series of waypoints forming the fastest path between the origin and destination addresses, as determined by the Google Maps Directions API [30]. These waypoints are then subsampled linearly. The Google API causes the user to walk realistic paths, as the waypoints are on walkable routes, such as sidewalks. To eliminate discontinuous changes in direction of travel, the user is modeled to always walk toward the point that is 2 m ahead on the straight path, subsampling the path every wavelength. The final path can clip with the environment, in which case the points are discarded. The elevation of the points follows the terrain. 1.5 m is added to this elevation to take the average height of the UE into account. The user walks at a constant speed of 1.4 m/s. Each point along the path is timestamped in order to average fields along time.

Antenna locations in a 5G network: The realistic locations of 5G BSs are not available on a global scale. One possible solution is open services that aggregate BS locations based on GPS location and signal strength through crowd-sourcing. For this chapter, the OpenCellID API [31] provides the location of real cellular BSs with high coverage. Locations are determined using crowd-sourced data. Therefore, the accuracy depends on the number of measurements and the propagation model used to triangulate BSs positions. Only the antenna density is representative of the physical twin. This is illustrated in Fig. 4.1(a) with red dots.

Antenna locations in a 6G network: A 6G CF-MaMIMO access-point network (APN) is a system that comprises a very large number of distributed APs which simultaneously serve a much smaller number of users over a wide area [2, 5]. Here, APs are placed on the facades of buildings. First, building mesh faces located 3 meters above the ground and whose normals have azimuthal angles between 70 and 90 degrees are selected. Then, uniform Poisson disc sampling with a minimum distance of 10 m is performed using the efficient Bridson's algorithm [32]. 1.5 m above the nearest ground mesh, vertically-polarized omnidirectional antennas model the UE (e.g. a smartphone) being held by the pedestrian.

4.2.2 Propagation step

A flowchart of the propagation step is detailed in Fig. 4.3. The upper box refers to the output of the configuration step in Fig. 4.2. In the central box, the propagation step combines RT and QuaDRiGa simulations for the LSF and small-scale fading (SSF) modelling of the channel, respectively. These are post-processed and form the input for the hybridization step shown on the bottom right (Fig. 4.4).

In summary, from the configuration step, the Rx's along the path, the environment and the Tx's antenna elements are loaded in. This forms the input for RT simulations evaluated for all Rx's and Tx's for every 1 m along the path. The output is the LSF channel and the 7 large-scale parameters (LSPs) for each point along the coarse path. Using QuaDRiGa, the path is split into segments. Within each segment, the LSPs are statistically aggregated to form the input for the QuaDRiGa computation along the fine path. The output is the SSF channel and the last-bounce scatterers (LBSs). In a post-processing step, the former is combined with the LSF

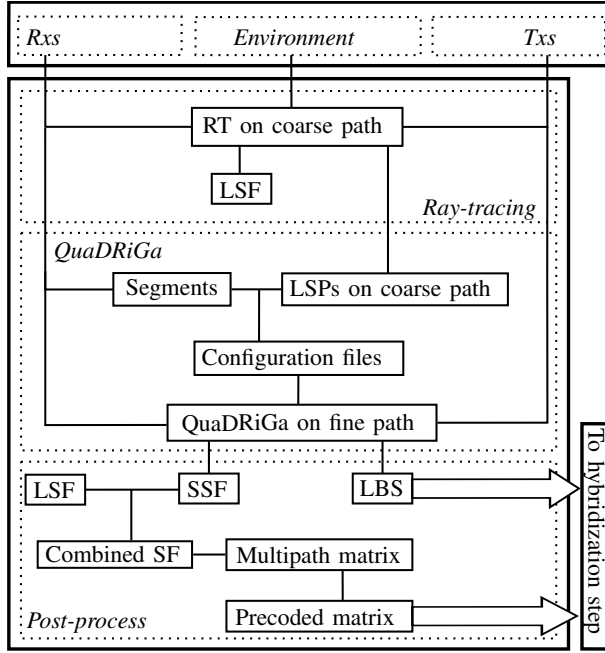


Figure 4.3: Flowchart of the propagation step.

channel to obtain the *multipath matrix*, with entries for 4 dimensions: receivers i , antenna elements j , LBSs l and distance snapshots s . Precoding is applied to the transmitted symbols. A *precoded multipath matrix* and the LBSs form the input for the hybridization step.

The propagation step involves simulating the wireless channel based on the configuration, defining all TxS, RxS and the 3D environment between them. Channel models can be broadly classified into deterministic and stochastic models. Based on the survey in [33], the SOTA among these channel models are selected.

Ray-tracing: RT is a deterministic channel modeling technique. In shooting and bouncing rays (SBR) RT, rays shoot out from the TxS, propagate and scatter through the environment, and are collected at the RxS. The advantage of RT is its potential to exactly model the underlying electromagnetic field problem in the high frequency limit, especially suitable for 5G and 6G mmWave channel models. Therefore, RT enables site-specific simulations that can match the corresponding measurements [34]. An important disadvantage of the method is the need for an accurate description of EMF scattering properties for different materials in the scene [23]. The data on this remain sparse in the literature. Moreover, the LoD for the meshes must be in the order of the wavelength [20]. This requires a fine semantically classified environment at mmWave frequencies. All these factors cause the accuracy of the CIR to be insufficient for large scale RT simulations. RT is also more computationally demanding compared to stochastic or map-based

Table 4.1: Constitutive parameters for the six material classes used in ray tracing at 28 GHz [36, 37]. PEC denotes a perfect electric conductor.

Material class	ϵ_r	σ (S/m)
Buildings (concrete)	5.24	0.6260
Terrain (asphalt)	5.7	5×10^{-4}
High vegetation	10	0.1
Cars	PEC	PEC
Water	80	4
Boats	PEC	PEC

channel models. Derived parameters such as the LSPs and their correlation matrix agree more robustly with measurements than the CIR. RT simulations are done every meter along the path.

The commercial solver Wireless Insite [35] is employed to perform the RT simulations. The Tx, Rx, and semantically classified environments are imported into the software. The six classes of materials are assigned the homogeneous constitutive parameters in Table 4.1. The SBR method is employed with 5 reflections, 1 diffraction, and 0 transmissions. A sensitivity study showed that increasing the interaction limits beyond these values changed the received power by less than 2%. The maximum angular separation between rays at the transmitter is 0.25° . The radius of the collection sphere at the receiver is 20 cm. Diffuse scattering was not modeled.

QuaDRiGa adds stochastic subclusters to represent unresolved channel diversity. Site-specific diffuse scattering and material variation within a class may affect reflected power and its angular distribution, particularly in shadowed regions. For each combination of i , j and s , $N_{i,j,s}^{\text{rays}}$ rays are retained if their power is at least -250 dBm at the receiver. The result is cast in a *multipath matrix* $\mathbf{M}^{\text{RT}}$ with dimensions $N \times M \times (\max N_{i,j,s}^{\text{rays}}) \times N_{\text{snapshot}}^{\text{RT}}$.

Here, $N_{\text{snapshot}}^{\text{RT}}$ is the number of ray-tracing snapshots along the coarse receiver path.

QuaDRiGa: The QuaDRiGa tool is used to generate realistic quasi-deterministic impulse responses from each AP to each receiver over time. QuaDRiGa is a quasi-deterministic channel model, but is classified as GSCM with a large number of features [33]. Configuration files containing the stochastic information from measurement campaigns in LOS/NLOS urban/suburban environments are available in the software. Based on these, a spatially-consistent stochastic parameter map of the LSPs is generated within each channel scenario [25]. Within segments along the path, stationary scattering clusters are generated around the receiver with properties that correspond to the parameter map. With the positions of the clusters known, a deterministic channel is obtained along the path of a moving user. This open-source model and its previous iterations have been validated for over two decades and comply with the 3GPP guidelines [38]. This tool was chosen as a

component of our numerical pipeline for three reasons. First, QuaDRiGa provides realistic channels because the statistical parameters that generate parameter maps are derived from measurement campaigns [25, 39]. In addition, version 2.0 features spatial consistency in the channels, which is important when modeling the resulting exposure along a path [40, 41]. Finally, the channel generator is computationally more efficient than deterministic methods to model the large number of channels in CF-MaMIMO scenarios.

In the RT-assisted case, ray tracing supplies channel information at one-meter intervals. QuaDRiGa generates the evolving multipath realization between these points. The coarse RT results constrain the amplitude variation and segment statistics. The resulting field remains a stochastic representation of unresolved multipath.

A number of LBS clusters, each with a number of subclusters, are generated around the user. The birth and death of clusters together with interpolations of their positions and powers also assure spatial consistency in the transitions between channel scenarios. Therefore, the hot-spot shape and exposure metrics consistently conform to the path and environment variations. Subclusters improve the realism of the channel clutter effect, by representing sub-resolution objects that accurately reproduce the LSPs from measurements. Computing the fields emitted from each subcluster is too computationally expensive. Instead, at most $N_{i,j,s}^{\text{subclusters}}$ beams with the greatest power are selected for a combined channel. $N_{i,j,s}^{\text{subclusters}}$ is chosen such that 99% of the power is accounted for in selected subclusters. Unselected subclusters have their total power (1%) spread uniformly over the selected ones. Multi-user scenarios can be implemented by defining an origin and destination address for each receiver and repeating the above steps. The QuaDRiGa software is modified to yield a multipath matrix $\mathbf{M}^{\text{QD}}$ with dimensions $N \times M \times (\max N_{i,j,s}^{\text{subclusters}}) \times N_{\text{snapshot}}^{\text{QD}}$, and the positions of the subclusters at each snapshot.

Here, $N_{\text{snapshot}}^{\text{QD}}$ is the number of QuaDRiGa snapshots along the fine receiver path.

Hybrid QuaDRiGa/FDTD that is not based on RT uses the configuration files of the mmMAGIC model, valid for frequencies above 6 GHz, a UE height of 1.5 meters and a Tx height of 6 to 10 meters [42]. For each point in the path, we manually assign a channel scenario based on the type of environment, e.g., dense urban, suburban, or rural. For each Tx, if the LOS connection is obstructed, the channel scenario is classified as NLOS and vice versa.

Ray-tracing based QuaDRiGa: The earlier 28 GHz RT/FDTD exposure study is described in [43]. This enabled a realistic, site-specific evaluation of the exposure metrics on humans in a factory-of-the-future. Hybrid RT/FDTD is computationally challenging because the full EMFs for many direction of arrivals (DoAs) need to be loaded into memory [43]. This challenge was alleviated by introducing a Huygens' box as an interface; the resulting method was applied to a small region in NYC in [15]. Despite improvements in efficiency, RT remains computationally demanding for environments larger than 100 m².

QuaDRiGa was hybridized for the first time with the FDTD method in [24]. The propagation step could then be computed faster and with more APs than with hybrid RT/FDTD. This enables the computation of exposure on the city scale, with an order of magnitude more APs and users. However, results can only be interpreted statistically over a large number of samples. Due to the stochastic nature of GSCMs, the site-specific geometry is lost with the exception of environment classification into LOS/NLOS and urban/sub-urban/rural.

This chapter introduces for the first time a new hybrid propagation model: *RT-based QuaDRiGa*. Falling under the map-based deterministic channel classification [33], this model represents the SOTA in the wireless channel modeling literature by combining the benefits of both deterministic and stochastic models. Previous research has focused on substituting RT with QuaDRiGa using appropriate LSPs [44]. This chapter presents a method to retain the physical accuracy of RT while leveraging the speed of QuaDRiGa. Points every 1 meter along the path of each user are chosen to evaluate the LSF variations in the environment. RT simulations compute the 8 LSPs used in QuaDRiGa [41] for these points. QuaDRiGa splits the path for each receiver in segments. The length of segments is drawn from a normal distribution with a mean of 40 m, a standard deviation of 5 m, and minimum/maximum of 30/70 m, respectively [42]. A new segment is also created when the receiver transitions between the LOS and NLOS states. Within these segments, the 7 LSPs (shadow fading is not considered) are aggregated statistically by computing the log-normal mean, standard deviation, decorrelation distances and inter-parameter correlation matrices. These form the stochastic basis for the QuaDRiGa method. The data is collected in configuration files.

The seven retained parameters are RMS delay spread, Ricean K-factor, azimuth and elevation spreads at departure and arrival, and cross-polarization ratio. Shadow fading is excluded. Their segment distributions, decorrelation distances and cross-correlations form the QuaDRiGa configuration. The coarse RT channel also supplies the separate amplitude target in Eqs. (4.2)–(4.5). Such configuration files are generally used to characterize different radio environments classified by urbanicity. Then, QuaDRiGa computes the channel along the full path, capturing the SSF variations. For each Rx/Tx link, the LSF and SSF parts are combined.

Now, it is possible to construct the combined multipath matrix $\mathbf{M} \in \mathbb{C}^{N \times M \times L \times S}$ with $L = \max_{i,j,s} N_{i,j,s}^{\text{subclusters}}$ and $S = N_{\text{snapshot}}^{\text{QD}}$. In general, the corresponding channel matrix $\mathbf{H}_s$ for snapshot s is the sum over either all subclusters in QuaDRiGa or all collected rays in RT in a link between receiver i and transmitter j :

$$\mathbf{H} = \sum_l \mathbf{M}_l. \quad (4.1)$$

$\mathbf{H}^{\text{QD}}$ and $\mathbf{H}^{\text{RT}}$ are interpolated and combined to form $\mathbf{H}^{\text{RT/QD}}$. Consider a path segment that starts at distance a and ends at distance b . The QuaDRiGa channels $\mathbf{H}_s^{\text{QD}}$ are evaluated at distances $s\delta d$, whereas the ray-tracing channels $\mathbf{H}_n^{\text{RT}}$ are evaluated at $n\Delta d = nq\delta d$, with $q = N_{\text{snapshot}}^{\text{QD}}/N_{\text{snapshot}}^{\text{RT}} \gg 1$. The QuaDRiGa

channel is first adjusted to meet the ray-tracing channel at both segment boundaries:

$$\begin{aligned} \hat{\mathbf{H}}_s^{\text{QD}} = \mathbf{H}_s^{\text{QD}} + \frac{s\delta d - a}{b - a} \left(\mathbf{H}_{b/\Delta d}^{\text{RT}} - \mathbf{H}_{b/\delta d}^{\text{QD}} \right) \\ - \frac{s\delta d - b}{b - a} \left(\mathbf{H}_{a/\Delta d}^{\text{RT}} - \mathbf{H}_{a/\delta d}^{\text{QD}} \right), \quad a \leq s\delta d \leq b. \end{aligned} \quad (4.2)$$

This adjustment is repeated for every path segment. Subtracting a moving average isolates the SSF variation:

$$\tilde{\mathbf{H}}_s^{\text{QD}} = \hat{\mathbf{H}}_s^{\text{QD}} - \frac{1}{2u} \sum_{s'=s-u}^{s+u} \hat{\mathbf{H}}_{s'}^{\text{QD}}, \quad u \leq s \leq S - u, \quad (4.3)$$

where $u = q/2$. The final channel adds the SSF variation to the ray-tracing channel interpolated on the fine grid:

$$\mathbf{H}_s^{\text{RT/QD}} = \mathbf{H}_{s,\text{interp}}^{\text{RT}} + \tilde{\mathbf{H}}_s^{\text{QD}}. \quad (4.4)$$

The final multipath matrix is obtained by:

$$\mathbf{M}_l = \mathbf{M}_l^{\text{QD}} \odot |\mathbf{H}^{\text{RT/QD}}| \oslash |\mathbf{H}^{\text{QD}}|, \quad (4.5)$$

where $\odot$ and $\oslash$ are the Hadamard element-wise multiplication and division operators. The rescaling sets the magnitude of the summed link channel to the RT-based target and leaves the phases of the QuaDRiGa realization unchanged. The target includes the QuaDRiGa small-scale residual. Cluster directions and relative powers remain those of the generated realization. The RT-derived parameters constrain the channel statistics and amplitude variation along the route, while the exact multipath geometry remains stochastic.

Precoding: When computing the downlink exposure from a CF-MaMIMO 6G system, the study in [24] assumed that every AP holds one antenna. However, these systems integrate multiple antenna elements within each AP. This is the case, e.g., in RSs. Due to the small wavelength at mid to upper mmWave bands, up to sixteen elements fit within the thin stripes, as is envisioned for 6G. Based on this, this chapter presents results for a large number of APs of 4×4 patch antennas at 28 GHz, distributed in the environment. We consider a noiseless channel where each antenna element radiates with phases and amplitudes $\mathbf{x} \in \mathbb{C}^{M \times 1}$ and each UE receives a signal $\mathbf{y} \in \mathbb{C}^{N \times 1}$

$$\mathbf{y} = \mathbf{H}\mathbf{x}. \quad (4.6)$$

As precoding is performed similarly for each snapshot s , this index is omitted for clarity.

At each snapshot, the precoder uses the modeled channel without estimation error or delay. The antenna elements and APs are assumed to have the relative phase synchronization required for coherent transmission. Therefore, the results describe ideal coherent precoding for this channel and power allocation. Precoding

is performed with MRT normalized to a power P using vector normalization. The precoding matrix $\mathbf{W}$ is [45]

$$\mathbf{W} = \sqrt{\frac{P}{N}} \begin{bmatrix} \mathbf{f}_1 & \cdots & \mathbf{f}_N \end{bmatrix}, \quad (4.7)$$

where $\mathbf{f}_i$ are column vectors of the hermitian conjugate of the channel.

For the user/non-user pair, $N = 2$: one user is active and the other is a non-user. The transmitted symbol vector is $[1, 0]^T$. The model applies precoding in two stages. The first stage sets the relative element weights within each AP. The second stage coordinates the phase and amplitude of the AP outputs across the network.

In the first step, the powers and phases of each element in the 4×4 arrays are tuned to beamform toward the user. For an AP $J = 1, \dots, \mathcal{M}$ that contains the antenna elements j with indices $\mathcal{J}(J)$, the entries of its associated precoding matrix are

$$w_{j,i}^J = \begin{cases} \frac{h_{i,j}^*}{\sqrt{N \sum_j |h_{i,j}|^2}} & \forall j \in \mathcal{J}(J) \\ 0 & \forall j \notin \mathcal{J}(J) \end{cases}, \quad (4.8)$$

where $P = 1$ W. The phases and amplitudes of the antenna elements are independently added for each AP

$$\hat{\mathbf{x}} = \sum_J \hat{\mathbf{x}}^J = \sum_J \sum_i \mathbf{w}_i^J s_i, \quad (4.9)$$

where $s \in \mathbb{C}^{N \times 1}$ is the transmitted symbol. However, the phases and amplitudes are not final, as denoted by a hat, because there is no coordination between the APs yet. The received signal from AP J is

$$\hat{\mathbf{y}}^J = \mathbf{H} \hat{\mathbf{x}}^J, \quad (4.10)$$

or for each subcluster

$$\hat{\mathbf{y}}_l^J = \mathbf{M} \hat{\mathbf{x}}^J. \quad (4.11)$$

We can now define an intermediary multipath matrix $\hat{\mathbf{M}} \in \mathbb{C}^{N \times \mathcal{M} \times L \times S}$ which embeds these phases and amplitudes in its matrix elements:

$$\hat{M}_{i,J,l,s} = \hat{y}_{i,J,l,s}. \quad (4.12)$$

In the second step, the phases and amplitudes of APs as a whole are tuned to beamform toward the user. The precoding matrix $\mathbf{W}$ of the entire APN is defined as in (4.7) but with

$$\mathbf{F} = \hat{\mathbf{H}}^H, \quad (4.13)$$

where $\hat{\mathbf{H}}$ is the intermediary channel computed with (4.1). All exposure results are linear w.r.t. the total power P allotted to the network in (4.7). The final phases and amplitudes of all antenna elements in the APN are

$$\mathbf{x} = \sum_i \mathbf{w}_i s_i. \quad (4.14)$$

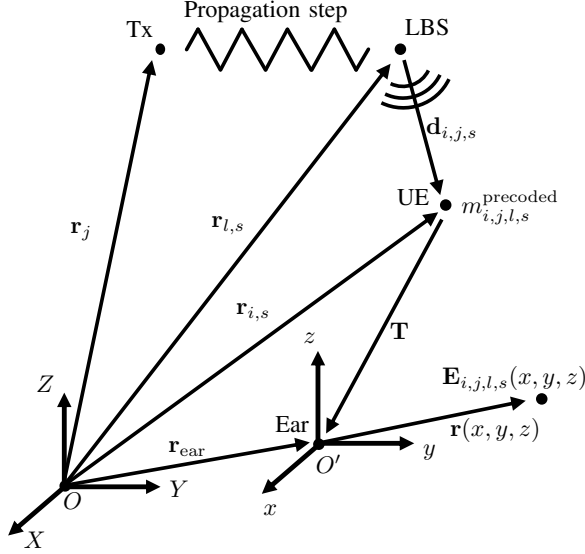


Figure 4.4: Overview of vectors related to the hybridization step.

The final *precoded multipath matrix* similarly embeds the transmitters' phases and amplitudes with symbol s such that its entries are the received signal at the UEs:

$$m_{i,j,l,s}^{\text{precoded}} = \hat{m}_{i,j,l,s} \cdot x_{j,s}. \quad (4.15)$$

The precoded case will be compared with the *unprecoded* case. Here, $h_{i,j}$ and $f_{i,j}$ in (4.8) and (4.13) are set to $\exp j\phi_{i,j}$, where $\phi_{i,j}$ are random values drawn from $[0, 2\pi)$. As the precoding acts on a completely different channel, the phases and amplitudes $x^{\text{unprecoded}}$ will no longer cause beamforming toward the user. The final unprecoded multipath matrix is

$$m_{i,j,l,s}^{\text{unprecoded}} = \hat{m}_{i,j,l,s} \cdot x_{j,s}^{\text{unprecoded}}, \quad (4.16)$$

where $x_{j,s}^{\text{unprecoded}}$ arises from a normalized precoding matrix. MRT precoding cannot place a null on a non-user. A non-user can however experience increased exposure when entering the LSF hot-spot from an active user. Hence, the case of unprecoded transmission, where beamforming is disabled, is comparable to a non-user scenario when aggregated over many samples.

4.2.3 Hybridization step

The geometry of the hybridization step is shown in Fig. 4.4. A global coordinate system O defines the positions of an antenna element j in a MIMO BS (Tx), a QuaDRiGa LBS l at time-snapshot s , the antenna of the UE held by user i at time

snapshot s , and the center of the evaluated exposure region (Ear) at time snapshot s . This center defines a new moving coordinate system O' , parallel to O and translated by $\mathbf{r}_{\text{ear}}$. The final electric field $E_{i,j,l,s}(x, y, z)$ is defined in O' and emanates from the LBS (one of the scatterers in a QuaDRiGa cluster). The indices i, j, l, s form a combination of Rx, Tx (element), subcluster LBS and distance snapshot, respectively, for which the electric field is computed. The Huygens' box function within the numerical pipeline is illustrated in Fig. 4.1(b). A Huygens' surface is used as an interface with the exposure step, requiring saving the fields only on the surface of the box [46].

First, we describe the approach in free space. Section 4.2.4 will consider the case where the channel is altered because the impinging fields are scattered by the anatomical phantom. For a vertically-polarized omnidirectional receiving antenna, the channel in (4.5) can be related to the electric field at the UE.

The idealized receiver senses the field component along $\mathbf{e}_\theta$ for each arrival direction. The antenna factor A_F is the ratio of that incident field component to the received terminal voltage for the chosen receiver load, with units m^{-1} . Equation (4.17) uses its inverse to convert the field component into the receiving-port response. The same conversion is reversed in (4.20) before the path fields are summed on the Huygens box.

$$m_{i,j,l,s}^{\text{precoded}} = \frac{1}{A_F} \mathbf{E}_{i,j,l,s}(-\mathbf{T}) \cdot \mathbf{e}_\theta(\theta_{i,l,s}, \phi_{i,l,s}), \quad (4.17)$$

where A_F is the antenna factor in m^{-1} of the omnidirectional antenna, θ and ϕ angles are the spherical coordinates of the impinging electric field $\mathbf{E}_{i,j,l,s}$ on the UE and $\mathbf{e}_\theta$ is the unit vector along θ . This expression holds true at the antenna of the UE. The total fields are now computed on the bounding box around the location of the user's right ear. Their coordinates $\mathbf{r}(x, y, z)$ are with respect to a new origin O' at $\mathbf{r}_{\text{ear}} = \mathbf{T} + \mathbf{r}_i$, where $\mathbf{T}$ is the translation between the UE's antenna and the ear. In O' , the electric field's spatial component ξ in the far-field from a subcluster to $\mathbf{r}(x, y, z)$ behaves as

$$\xi(x, y, z) = A \frac{\exp(jk |\mathbf{d}_{i,l,s} + \mathbf{T} + \mathbf{r}(x, y, z)|)}{|\mathbf{d}_{i,l,s} + \mathbf{T} + \mathbf{r}(x, y, z)|}, \quad (4.18)$$

where $\mathbf{d}_{i,l,s} = \mathbf{r}_{i,s} - \mathbf{r}_{l,s}$ and A is its amplitude, normalized to unity at the UE

$$A = \exp(-jk |\mathbf{d}_{i,l,s}|) |\mathbf{d}_{i,l,s}|. \quad (4.19)$$

An expression can be constructed for the electric field around the UE:

$$\mathbf{E}_{i,j,l,s}(x, y, z) = A_F m_{i,j,l,s}^{\text{precoded}} \xi(x, y, z) \mathbf{e}_\theta(\theta_{i,l,s}, \phi_{i,l,s}). \quad (4.20)$$

By summing over all Txs and subclusters, the total EMFs are obtained

$$\begin{aligned} \mathbf{E}_{i,s} &= \sum_{j,l} \mathbf{E}_{i,j,l,s}, \\ \mathbf{H}_{i,s} &= \sum_{j,l} \frac{1}{Z_0} \frac{\mathbf{d}_{i,l,s}}{|\mathbf{d}_{i,l,s}|} \times \mathbf{E}_{i,j,l,s}. \end{aligned} \quad (4.21)$$

These fields are evaluated on the sides of the Huygens' box on the same Yee-grid as the FDTD simulation. Hence, the computational and memory requirements scale quadratically with frequency instead of cubically.

4.2.4 Exposure step

Absorbed power density: The function of the exposure simulation within the numerical pipeline is illustrated in Fig. 4.1(b). MRT precoding of the symbols causes the transmitted beam's direction of maximal gain to be aligned toward $\mathbf{r}_{i,s}$, in particular for LOS and collocated antennas [43]. This is a *large-scale hot-spot*, which can induce higher fields to nearby non-users. In addition, alignment of the amplitudes and phases from different beams causes an additional hot-spot gain at $\mathbf{r}_{i,s}$ if $\mathbf{r} = -\mathbf{T}$. This is the *small-scale hot-spot* and is studied in detail in this chapter. As reference quantities are determined in free-space receiving scenarios, the time-averaged incoming power density S_{inc} is readily available. However, to compute the basic quantities, an anatomical phantom is included in the FDTD simulations, which invalidates (4.17) and eliminates the small-scale hot-spot effect. This user-induced coupling is included here based on [47], but with the rays substituted by QuaDRiGa subclusters. The FDTD simulations themselves are performed similarly to those in [43], but with efficiency and accuracy improvements. The result is the absorbed power density along the path.

For the coupling calculation, a vertical electric edge source is placed 1 cm from the tip of the right ear and excited with 1 V. Reciprocity between transmitting and receiving antennas [48] gives the vertically polarized antenna pattern $A^\theta(\theta, \phi)$ in the presence of the anatomical phantom. The coupled channel is

$$c_{i,j,l,s}^{\text{coupled}} = A^\theta(\theta_{i,l,s}, \phi_{i,l,s}) c_{i,j,l,s}^{\text{uncoupled}}. \quad (4.22)$$

Bilinear interpolation gives A^θ between the simulated angles. The antenna pattern is computed once for a given exposure configuration, and precoding is applied after the channel is coupled.

The Huygens' surface provides generalized total-field/scattered-field sources for an FDTD simulation that contains the MIDA anatomical phantom [49]. The phantom has an isotropic spatial resolution of 500 μm , and the Huygens' surface uses at least ten cells per wavelength. At 28 GHz, the penetration depth is approximately 0.92 mm, or $\lambda/10$ [10]. A coated dielectric skin model therefore resolves the superficial exposure efficiently [50, 51]. Post-processing computes the maximum S_{ab} averaged over 4 cm^2 [52]. GPU-accelerated HPC and a weak time-convergence criterion reduce the computation time.

Hot-spot characterization: In [15], the shape of a hot-spot was studied in an experimental setup. The hot-spot features a large-scale hot-spot around the receiver, a small-scale hot-spot as a result of the interference pattern, prominent sidelobes and spherical wavefronts. Similar results are seen at 3.5 GHz [14]. The aforementioned study validated the hybridization part of our tool because the experiment matched the simulation well.

Two methods to define the location of hot-spots are examined. First, exactly where the UE is located and second, where the fields are highest in a small region around the UE. At this location, three slices are taken normal to the x -, y - and z -planes. A peak-finding algorithm detects whether a hot-spot is present along each axis. We introduce three properties to characterize the hot-spots:

1. The *dimensionality* of a hot-spot is the number of axes where a hot-spot was found.
2. The full width at half maximum (FWHM) is the average of all detected FWHMs.
3. The prominence-to-peak (P/P) ratio provides a representation of the hot-spot's dynamic range, where a ratio of 1 corresponds to a peak flanked by fields equaling 0.

Two methods are proposed to average exposure metrics over time. In the first method, the exposure metrics S_{inc} and S_{ab} are considered for each time step in the walk. The average exposure metrics are then the average of all these over time. This is coined *exposure-wise* averaging, because the concept of “exposure at each time step” is correctly interpreted. When computed over a 6-min interval, these averages correspond to the ICNIRP time-averaged exposure metrics. In the second method, the average of the electric and magnetic fields over time is considered first. The average exposure metrics S_{inc} and S_{ab} are then computed for these average EMFs. This is coined *propagation-wise* averaging, because the concept of “average propagated EMFs” is correctly interpreted. These maps show the coherent focusing pattern. Field cancellation between snapshots affects this view. For example, (E, H) and $(-E, -H)$ have equal power but zero mean fields. For an exposure average, power is calculated at each snapshot before averaging. Thus, the equations for incident power density are the following:

$$\begin{aligned} S_{\text{inc,exposure-wise}}(\mathbf{r}) &= \langle |\mathbf{E}(\mathbf{r}) \times \mathbf{H}(\mathbf{r})| \rangle, \\ S_{\text{inc,propagation-wise}}(\mathbf{r}) &= |\langle \mathbf{E}(\mathbf{r}) \rangle \times \langle \mathbf{H}(\mathbf{r}) \rangle|, \end{aligned} \quad (4.23)$$

where $\langle \cdot \rangle$ is the average of a quantity with respect to time. Analogous formulas apply for S_{ab} .

Exposure limits: In order to prevent excessive heating, the ICNIRP guidelines [10] define limits for the reference and basic quantities. For the general public at 28 GHz, the local basic restriction is determined by S_{ab} averaged over a square 4 cm^2 body-surface area and 6 min, which should not exceed 20 W/m^2 . The corresponding local reference level for S_{inc} is $55/28^{0.177} \approx 30.5 \text{ W/m}^2$, averaged over a square 4 cm^2 projected body-surface area and 6 min. The separate whole-body reference level is 10 W/m^2 with a 30-min average.

Far-field exposure, including exposure from MaMIMO technology, will typically induce highly non-uniform exposure patterns within intervals shorter than 6 min. In this case, the relevant exposure metric is integrated over time and compared with the brief local exposure limits [10]. We compare the instantaneous

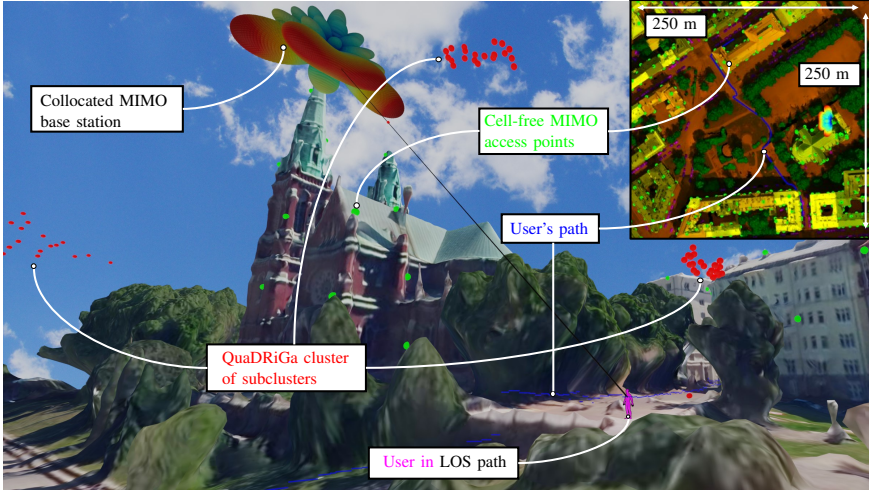


Figure 4.5: Configuration of the Helsinki case study. A CF-MaMIMO network (green) is simulated. Alternatively, a collocated MIMO BS beamforms toward the user (purple) at a snapshot on a LOS path (black). At this snapshot, the QuaDRiGa clusters, composed of subclusters (red), are shown (acting in free space). The inset depicts the user's path (blue) walking from bottom to top.

exposure metrics along the walks with the power-density limits. If the spatially averaged power stays below the local threshold throughout an interval, its integrated energy also satisfies the brief-exposure limits. The incident-power ratios in the figures use 10 W/m^2 , below the local incident reference level at 28 GHz.

Moreover, compliance with the reference levels is assumed to imply compliance with the basic restrictions. The relevant literature uses computational methods to assert this point under simplified and worst-case incidence assumptions. Therefore, it is sufficient to demonstrate compliance with only the reference levels. However, our tool computes both reference and basic quantities, providing a unique insight into the validity of this assumption under realistic incidence conditions, offering the possibility to relax or tighten the reference levels based on its conclusions.

4.3 Results and discussion

Two case studies are examined and the ray-tracing component is only introduced in the second. The first shows the scalability of hybrid QuaDRiGa/FDTD. The second uses the complete pipeline in a site-specific urban model. Then, the localized exposure around the UE is studied.

4.3.1 Case study in Helsinki, Finland

In this case study, hybrid QuaDRiGa/FDTD is applied to a single-user scenario of a 6G cell-free massive MIMO network and compared with a 5G collocated MIMO antenna. Fig. 4.5 shows the configuration of this case study. The signals are precoded toward a smartphone held in the hand of a pedestrian. The user walks the blue path shown in the inset of Fig. 4.5, near St. John's Church in Helsinki. The total distance of the walk is 273 m. The pedestrian is in an urban environment in the first and last 50 m. In between, the user walks through the park of St. John's church in central Helsinki. Due to the increased vegetation and absence of buildings, the environment in this section is suburban. A collocated 8×8 MIMO antenna is placed on the tower of the church, facing south and tilted down by 15° .

The hybrid QuaDRiGa/FDTD method is applied with a carrier frequency of 28 GHz. The sampling rate is 53 Hz (such that there are 2.46 wavelengths between each snapshot) and the total number of distance snapshots (or evaluation points) is 9905. The $250 \text{ m} \times 250 \text{ m}$ area around the path contains 335 distributed APs. Each AP has a 4×4 array, giving 16 antenna elements per AP and 5360 antenna elements in total. The FDTD grid and Huygens' surface have a resolution of 15 cells per wavelength resulting in a grid of $302 \times 230 \times 323$ cells. The average computation time for one snapshot of hybrid QuaDRiGa/FDTD is 160 sec. In this case study, we choose $\mathbf{T} = -50 \text{ cm } \mathbf{e}_x + 50 \text{ cm } \mathbf{e}_z$, with the x -axis in the direction of travel and the z -axis in the vertical direction. This models holding a smartphone in front of the user's torso. Thus, including head-coupling is not necessary as no hot-spot gain is present. Note that the coupling is not necessary in free space when computing S_{inc} due to the experimental assessment procedure of reference quantities [10].

Fig. 4.6 shows the reference and basic quantities as a function of distance along the path. The exposure is compared for precoded (user scenario) and unprecoded (non-user scenario) transmission, and compared for cell-free and collocated MaMIMO. The left axis expresses the exposure for normalized powers per antenna element. This means that the normalized exposure metric $\hat{E}$ is

$$\hat{E} = \frac{E}{N_{\text{AE}}} , \quad (4.24)$$

where E is the exposure metric and N_{AE} equals 64 for the collocated antenna case or 335 for the distributed antenna case. The right axis expresses the ratio to the exposure limits for a typical total power of 320 W. This ratio η therefore equals

$$\eta = P \frac{\hat{E}}{E_{\text{limit}}} , \quad (4.25)$$

Here P is the total network power (320 W). In the plotted ratios, E_{limit} is 10 W/m^2 for incident power density and 20 W/m^2 for absorbed power density. For a local comparison at 28 GHz, the applicable 6 min thresholds are approximately 30.5 W/m^2 and 20 W/m^2 , respectively, with their respective square 4 cm^2 spatial averages. The maximum of these ratios is at most 0.05% for a collocated BS precoding the channel in a suburban LOS propagation environment. The range between

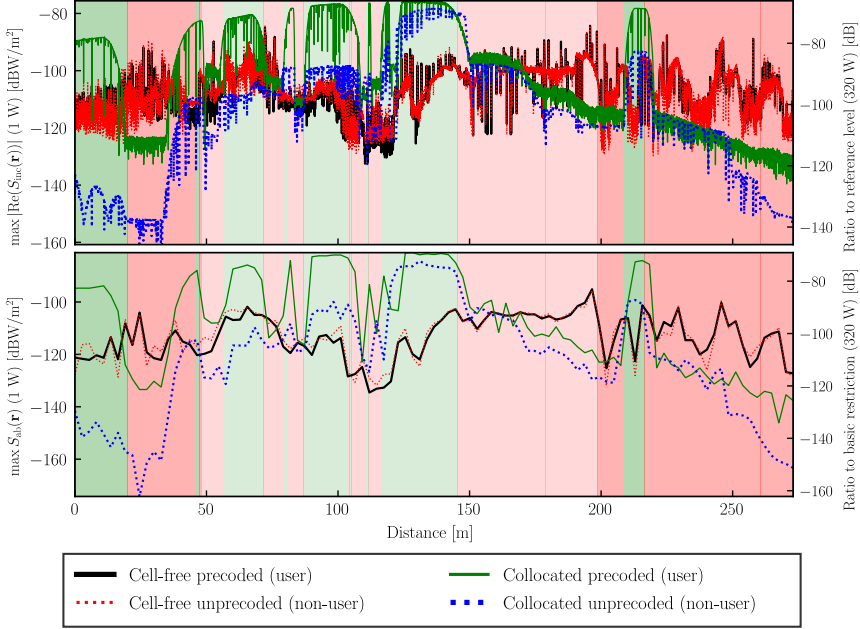


Figure 4.6: Reference (top) and basic (bottom) exposure quantities along the Helsinki path. Black solid and red dotted curves show cell-free transmission with and without precoding, respectively. Green solid and blue dotted curves show collocated transmission with and without precoding, respectively. Precoded and unprecoded transmission represent the user and non-user scenarios. Green and red background bands indicate LOS and NLOS relative to the collocated antenna. Darker and lighter bands indicate urban and suburban segments, respectively.

the minimal and maximal S_{ab} exposure is about 20 dB or 100 times greater with precoded transmission compared to unprecoded transmission, because the beams are steered in the direction of the user. This effect almost completely disappears for CF-MaMIMO, as can be seen in Fig. 4.6. At any time, only a few APs from different locations serve the user. The AP outputs are coordinated in phase and amplitude to focus the field toward the user. The dynamic range of S_{ab} is also 20 dB smaller for the CF-MaMIMO network than for collocated MIMO. This is because the path loss is highest at the start and end of the path. In these urban regions, the user is also in NLOS due to the obstruction of the buildings. The cell-free APN causes a more uniform exposure along the path because, most of the time, at least one AP is in LOS with the user. From a network planning point of view, more power can be fed to a 6G CF-MaMIMO system compared to a 5G collocated one, while avoiding regions of excessive exposure. Furthermore, we observe the continuity (that is, no abrupt jumps) of the channel over time for LSF and report continuity for SSF. The reference and basic exposure quantities expressed in dB have a moderate positive correlation, with a Pearson coefficient of approximately 0.60. A similar correlation was found in the earlier indoor study [43].

The dynamic range is the difference between the maximum and minimum exposure in dB along this route and is unchanged by a constant rescaling of network power at fixed relative precoding weights. We compare the deployments at the same total network power, without requiring equal coverage or communication performance.

4.3.2 Case study in New York City, USA

In this case study, RT-based hybrid QuaDRiGa/FDTD is applied to the urban scenario shown in Fig. 4.1(a). After spending 10 seconds indoors, a smartphone user walks from the One WTC tower southward to Liberty Street in NYC, staying indoors for another 10 seconds. The user passes by an open area with foliage. Cellular APs from neighboring buildings radiate onto the user below the tree cover in either LOS or NLOS. The QuaDRiGa channel model distinguishes and interpolates between these in a continuous fashion. The total duration of the walk is 6 minutes. In this case study, we choose $\mathbf{T} = \mathbf{0}$, corresponding to the user holding a smartphone by the right ear. Thus, including head-coupling is necessary as a hot-spot gain can be present.

The *user/non-user contrast* is defined as the average difference in signal gain between the two users walking 5 meters from each other. The transmit symbol $\mathbf{s} = [1 \ 0]^T$ is precoded such that the first user is a user and the second user is a non-user. Hence, a high user/non-user contrast shows functioning precoding and the extent of non-user exposure from a large-scale hot-spot created by beamforming. When precoding is applied only on antenna elements within each AP (as in (4.8)), the user/non-user contrast increases by 6.01 dB along the walk. All APs beamform toward the user, but the closest AP does not necessarily emit most of the power. When precoding is applied only on the APs themselves, the user/non-user contrast increases by 4.74 dB. None of the APs beamform toward the user, but the nearest

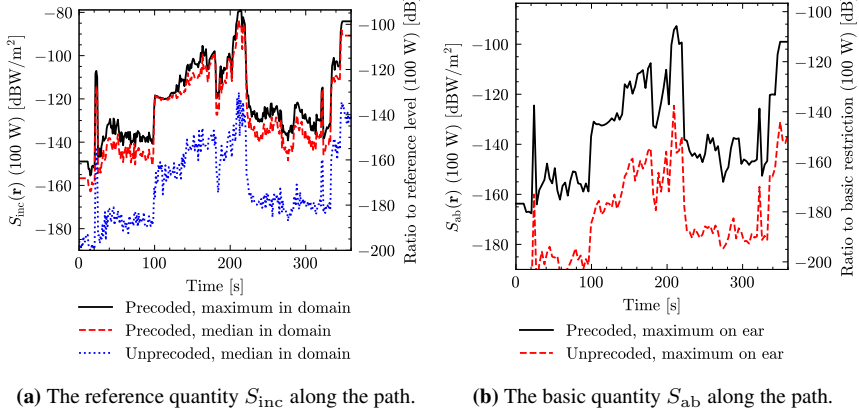


Figure 4.7: The reference (S_{inc}) and basic (S_{ab}) exposure quantities are plotted along the walk (left vertical axis). The right axis compares the snapshot values with 10 W/m^2 for incident power density and 20 W/m^2 for absorbed power density, as discussed in Section 4.2.4. The influence of the hot-spot is shown in free space.

AP emits most power. When both precodings are combined (equations (4.8) and (4.13)), the user/non-user contrast is 10.08 dB.

Fig. 4.7 shows the exposure metrics S_{inc} and S_{ab} along the walk on the left vertical axis. The maximum S_{inc} is compared with the median S_{inc} in the computational domain to illustrate the hot-spot gain. The precoded transmission case is compared with the unprecoded transmission case. The exposure is constant when the user is indoors. The exposure is continuous in time and consistent with the environment, e.g., the signal increases substantially when near APs and when the user is in LOS. The maximum incident and absorbed power densities are -78.8 dBW/m^2 (13.18 nW/m^2) and -92.8 dBW/m^2 (0.5248 nW/m^2), respectively, at a total network power of 100 W. The ratio of the exposure metric divided by the relevant ICNIRP exposure limit is shown on the right vertical axis.

4.3.3 Hot-spots

Within a large-scale region exposed by the beams, hot-spots can increase the aforementioned 10.08 dB gain locally, at or within several wavelengths of the receiver. A free-space domain of $4.76\lambda \times 3.83\lambda \times 6.63\lambda$ ($5.1 \text{ cm} \times 4.1 \text{ cm} \times 7.1 \text{ cm}$) is considered, fitting a human ear. The mean and standard deviation were computed based on 316 time steps along the walk.

The means of the FWHM and P/P ratios indicate a size on the order of one wavelength (10.7 mm) and a visible peak, respectively. The distance from the center for the point with the highest field is 2.63λ on average. However, the number of hot-spots found along the path per λ^3 is highest in the center. More than 50% of

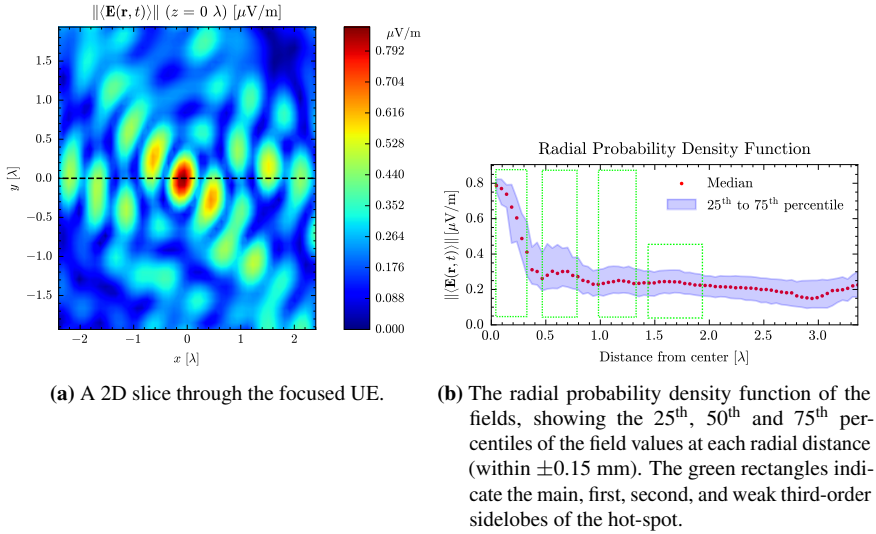


Figure 4.8: Visualization of a hot-spot's electric field when averaged propagation-wise (norm of the time-average).

the hot-spots are within 0.28λ of the center, with many outliers. As expected, the peak expresses high variability because of the log-normal distribution of received signals, as is typical in wireless channels. The standard deviations of the FWHM and P/P ratio are high, approximately 40% of their mean. When examining the field distribution along the walk step by step, the location and shape of the hot-spot change frequently, but in a continuous fashion due to the time-continuity of the propagation step. During 96% of the walk, the dimensionality is equal to 3, indicating a roughly ellipsoidal or spherical shape. The hot-spots vanish or are reduced to a simple interference pattern when one or two strong LOS components are present, respectively. They also vanish when no precoding is applied.

At any specific time step, a hot-spot can appear in a variety of shapes, sizes, and locations. However, a characteristic shape appears when the hot-spot is averaged in time. ICNIRP also specifies that exposure metrics should be averaged over 6-min intervals. Fig. 4.8(a) depicts a horizontal slice through the receiver, positioned in the center. In a first step, the electric field is examined because its norm appears in (4.23) for propagation-wise S_{inc} and the field itself is maximized through precoding. The main peak is located in the center with a FWHM of 0.44λ . The peak is flanked by troughs at 25% of its value, giving a ratio of 75% P/P (90% with the deepest troughs). A first-order sidelobe is observed at 0.61λ with a peak value equal to 50% of the main peak. A second-order sidelobe is observed at 1.15λ . Angular dependence is observed in the 2D slice, showing peaks and troughs for certain azimuthal angles. Fig. 4.8(b) shows the radial probability density function of the field with respect to distance. For a distance $r \pm dr$ measured from the center of the

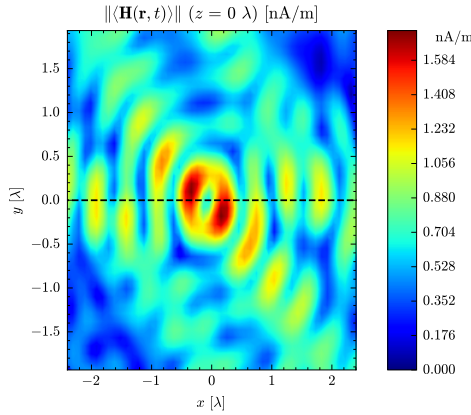


Figure 4.9: A 2D slice through the focused UE of a hot-spot's magnetic field when averaged propagation-wise (norm of the time-average).

FDTD domain, the field values are collected in a distribution. The graph displays the 25th, 50th, and 75th percentiles of this distribution as a function of r . The same main, first- and second-order sidelobes are observed (shown in green). A weak third-order sidelobe is observed at 1.76λ . This is weaker because the peaks and troughs are averaged out in the angular domain. As the distance approaches the edges of the domain, a constant field remains, which is 25% of the peak in the main lobe. Therefore, the small-scale hot-spot increases the electric field by 12 dB on top of the large-scale beamforming gain. Increasing the number of coherently controlled antenna elements can increase focal gain under ideal channel knowledge. The achievable gain depends on array geometry, propagation and total transmit power. Within each sidelobe, peaks and troughs appear as a function of the azimuthal and elevation angles.

The magnetic field of the hot-spot behaves analogously to a typical interference pattern: when the electric field reaches a peak in space, the magnetic field reaches a trough, and vice versa, as can be seen in Fig. 4.9. Fig. 4.10(a) shows S_{inc} for the 2D slice. The expression for S_{inc} combines the electric and magnetic fields. The hot-spot also combines the features of the electric and magnetic field hot-spots. The small peak at the center is the combination of an electric-field peak and a magnetic-field trough. This is flanked by higher peaks originating from the first-order magnetic-field sidelobes. The sidelobe series continues with alternating peaks from both fields.

With propagation-wise averaging, positive EMF vector components at one time step can cancel out negative EMF vector components at another time step. However, from an exposure assessment point of view, both positive and negative field values can contribute to dielectric heating. The exposure-wise average of S_{inc} is visualized in Fig. 4.10(b) in the same 2D slice. A less regular interference pattern is seen with its highest peak not at the center. The FWHM is 0.92λ and the P/P ratio is

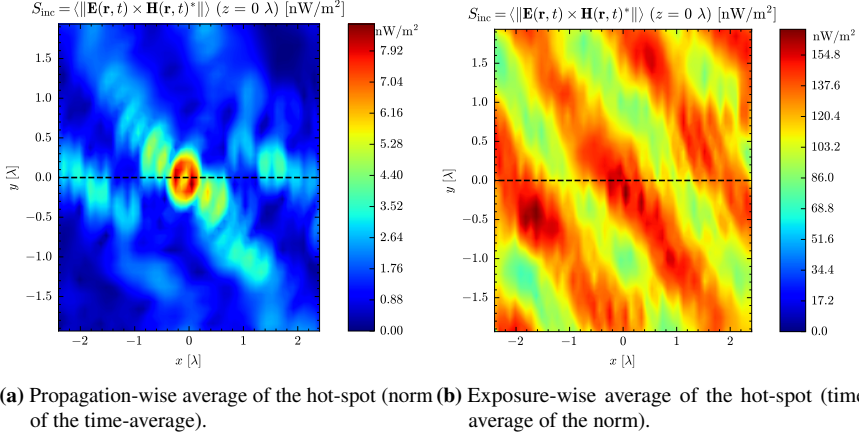


Figure 4.10: Comparison of S_{inc} under propagation- and exposure-wise averaging using 2D slices. The former averages the fields over time first; the latter computes the exposure first and then averages it over time.

37% with the deepest troughs. The pattern is overlaid on a constant envelope. This causes the first-order troughs to be 2.5 times shallower than with propagation-wise averaging.

4.4 Conclusion

In this chapter, we presented an RT-based hybrid QuaDRiGa/FDTD method to assess human exposure in realistic 6G CF-MaMIMO environments at 28 GHz. The method combines high-resolution 3D models of the environment, time-continuous channel simulations, precoding, and FDTD calculations with anatomical phantoms. The method thereby links network operation to the external reference levels and internal basic restrictions specified by ICNIRP.

The snapshot maxima in the Helsinki and New York case studies were below 1% of the local power-density thresholds. Compared with collocated MaMIMO, the cell-free system produced more uniform exposure along the receiver path and reduced its dynamic range by approximately 20 dB. The hot-spot analysis found a further 12 dB increase in the electric field at the focus of a precoded transmission. The location and shape of this hot-spot changed continuously with the propagation environment, and the time-averaged pattern had a characteristic size of the order of one wavelength.

Ray tracing of large urban scenes remains computationally demanding, and the angle of arrivals (AoAs) of QuaDRiGa clusters do not necessarily align with the actual propagation directions in the reconstructed environment. The method nevertheless traces exposure from transmit-power control to tissue absorption.

However, applying FDTD to even a single ear remains computationally prohibitive because its cost scales approximately as f^4 . In the next chapter, we remove this bottleneck with closed-form absorbed-power models for network-scale analysis.

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5

Closed-Form Absorbed-Power Dosimetry

“Oh, yes, the past can hurt. But the way I see it you can either run from it or learn from it.”

— Rafiki, *The Lion King*

This chapter is adapted from:

- Robin Wydaeghe, Luc Martens, Günter Vermeeren, Emmeric Tanghe, and Wout Joseph, “Closed-form absorbed-power dosimetry from 1 to 100 GHz,” manuscript submitted to *IEEE Transactions on Antennas and Propagation*.
- Robin Wydaeghe, Luc Martens, Günter Vermeeren, Emmeric Tanghe, and Wout Joseph, “Exposure-constrained beamforming with a closed-form body absorption operator,” manuscript submitted to *IEEE Transactions on Wireless Communications*.

In Chapter 4, we coupled site-specific propagation to full-wave dosimetry, but the full-wave step becomes expensive at mmWave frequencies as its cost grows approximately with the fourth power of frequency. In this chapter, we replace this repeated step with closed-form absorbed-power models. We first derive and validate an incoherent surface law. We then include the phase between propagation paths and extend the same law into a coherent exposure operator for exposure assessment and beamforming.

5.1 Introduction

Wireless exposure of the human body is regulated through whole-body and local basic restrictions in the ICNIRP 2020 guidelines [1], IEC/IEEE 63195, and IEEE C95.1. Whole-body exposure is expressed as mass-averaged SAR. The local metric changes from spatial-peak SAR below 6 GHz to surface-averaged APD above 6 GHz. Direct evaluation uses FDTD simulations on an anatomical phantom [2–5]. Resolving the submillimeter absorption layer at ten cells per wavelength sets a cell count of 10^8 at 6 GHz, growing to 10^{12} near 100 GHz. A simulation campaign that covers frequencies, postures, and incidence directions takes weeks on GPU clusters. Whole-body simulations above 30 GHz become computationally difficult [5]. This work shows that the surface absorbed-power map on a 10^4 -triangle body mesh reduces to one matrix-vector multiply, evaluated in under 10 ms on a modern GPU at any frequency from 1 to 100 GHz. The whole-body absorbed power reduces to only three precomputed scalars: the body mass, the body surface area, and the flux-weighted Fresnel transmission.

Several research groups capture this absorption with a single fitted coefficient [2, 3, 6–9]. The coefficient is defined in different ways, as an efficiency, a normalized cross-section, or a transmission, but in every study it falls between about 0.4 and 0.7 above 6 GHz. This shared range points to a single underlying closed-form quantity. Each coefficient is fitted separately for each phantom and frequency from an FDTD sweep or a chamber measurement, so the values are slow to obtain, they differ between studies, and they provide no gradients for design. No study writes them as one expression, and none treats a nonconvex body in closed form.

The first part of this chapter, the incoherent formulation, derives the closed form behind these coefficients. For human tissue with a high refractive index, the unpolarized Fresnel transmission becomes a near-constant scalar [10]. The local law then integrates over a nonconvex body through a generalized Cauchy identity from 1841 [11], with self-shadowing from ambient occlusion [12–14]. A layered correction in the fat layer covers the 3 GHz dip [7]. The five fitted coefficients are special cases of this expression. In the mmWave band it reproduces FDTD to within the tissue dielectric uncertainty of 7%, at a small fraction of the cost. Because it is also differentiable, antenna and beam design under exposure limits becomes a continuous optimization. Therefore, it reduces the number of required simulations in a design loop.

The downlink-body channel is multipath, and a single free-space direction cannot represent the phase between paths that becomes significant in the coherent regime. No closed-form, ray-traced exposure operator exists for the downlink-body problem. Such an operator must stay tractable at mmWave frequencies and physically accurate for the multipath downlink-body channel.

The second part of this chapter, the coherent formulation, includes that phase and derives the exposure operator from the same propagation paths as the communication channel. The incoherent law is its random-phase limit, so the two formulations form one progression from absorbed-power prediction to exposure-aware control.

To the best of the authors' knowledge, the contributions are as follows.

- We derive closed-form APD laws from Fresnel transmission on lossy biological tissue and integrate them over nonconvex anatomical meshes with a generalized Cauchy formula. Whole-body absorbed power reduces to a flux-weighted transmission scalar and a single ambient-occlusion scalar.
- Pseudo-Brewster compensation simplifies the law further for unpolarized incidence. TE/TM cancellation keeps the geometric approximation within a few percent over the relevant angular range.
- The absorbed-power map is differentiable end-to-end and is the first APD map to provide closed-form gradients. For a body mesh under many incident paths, the absorbed-power map is a single matrix-vector multiplication, evaluated in under 10 ms.
- Higher-order correction terms extend and delimit the closed form. A layered transmission term covers the sub-6 GHz whole-body comparison, whereas curvature, diffraction, and inter-body reflection terms bound the main higher-order errors.
- The theory is validated in four independent ways: Mie theory on lossy spheres, full polarization-aware Fresnel calculations on the Thelonious phantom, Sim4Life FDTD, and dosimetry literature across 108 volunteers and 5 FDTD phantoms.
- We derive the first closed-form downlink body-exposure operator with a reusable anatomical depth-integration kernel and coherent ray-traced propagation paths. We compute the kernel once per phantom and use it across scenes and arrays. The operator uses the same paths as the communication channel and requires no FDTD simulations.
- A formulation of a novel Exposure-Constrained Beamforming (ECBF) is provided for the general downlink problem with every applicable ICNIRP 2020 basic restriction active at once. The closed-form ECBF precoder [15] works unchanged with the analytical $\mathbf{Q}$ in place of the FDTD-computed matrix.
- An indoor-factory demonstration of the operator across the FR2 and FR3 bands, covering 27 648 scene-body-array items and 746 496 full-body maps.

Section 5.2 derives the incoherent absorbed-power model. Section 5.3 validates it and analyzes its errors, and Section 5.4 gives the compliance bounds. Section 5.5 discusses the computational structure, regulatory implications and regime of validity. Section 5.6 then includes the path phases and derives the coherent operator and beamformer. Section 5.7 evaluates the construction, and Section 5.8.1 discusses the combined implications.

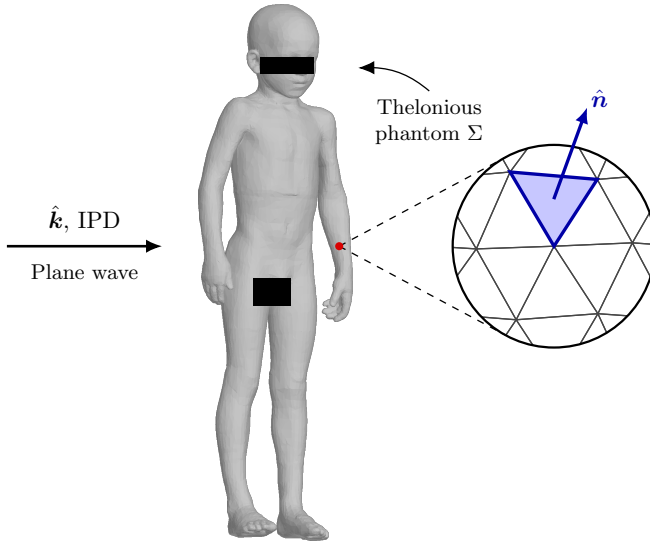


Figure 5.2: Configuration of the dosimetry problem. A plane wave with intensity IPD and direction $\hat{\mathbf{k}}$ illuminates the Thelonious phantom. The local APD at a visible surface point is $\text{APD} = \text{IPD } T(\theta) \cos \theta$, with θ the angle between $-\hat{\mathbf{k}}$ and the outward normal $\hat{\mathbf{n}}$ on the triangulated body surface, and T the Fresnel transmission.

are neglected at this stage and re-enter as bounded corrections in Sections 5.2.6 and 5.3.6. At a surface point $\mathbf{r}$ with outward unit normal $\hat{\mathbf{n}}(\mathbf{r})$, the incidence cosine is $\mu(\mathbf{r}) \equiv \hat{\mathbf{n}}(\mathbf{r}) \cdot (-\hat{\mathbf{k}}) = \cos \theta_i(\mathbf{r})$. A front-facing point has $\mu > 0$. A point facing away from the source has $\mu \leq 0$.

5.2.2 Power flux through the surface

The inward power flux through a surface element dA at $\mathbf{r}$ is $dP_{\text{in}} = \text{IPD } \mu dA$. The reflected wave propagates in the specular direction with power density $|r(\theta_i)|^2 \text{IPD}$, where $r(\theta_i)$ is the Fresnel amplitude reflection coefficient appropriate to the polarization. Energy conservation at a lossy half-space gives

$$\text{APD}(\mathbf{r}) = \text{IPD} \cdot T(\theta_i) \cdot \mu(\mathbf{r}), \quad T(\theta_i) \equiv 1 - |r(\theta_i)|^2, \quad (5.1)$$

for each polarization separately.

Here, T is the power transmission coefficient into tissue for the selected polarization.

5.2.3 Fresnel coefficients

The body surface is modeled as a planar interface between free space ($n_1 = 1$) and a lossy medium with complex refractive index $\tilde{n} = \sqrt{\varepsilon_r - i\sigma/(\omega\varepsilon_0)}$. The normal component of the wave vector inside the medium is $\xi = \sqrt{\tilde{n}^2 - 1 + \mu^2}$ with $\text{Re}(\xi) > 0$. Continuity of the tangential fields gives

$$r_s = \frac{\mu - \xi}{\mu + \xi}, \quad r_p = \frac{\tilde{n}^2 \mu - \xi}{\tilde{n}^2 \mu + \xi}, \quad (5.2)$$

where r_s and r_p are the Fresnel amplitude reflection coefficients for TE and TM polarization, respectively. The corresponding power-absorption coefficients are $T_s(\theta) = 1 - |r_s|^2$ and $T_p(\theta) = 1 - |r_p|^2$. At normal incidence, $\mu = 1$ and $\xi = \tilde{n}$, giving the polarization-independent normal-incidence value

$$T_0 \equiv T_s(0) = T_p(0) = \frac{4 \text{Re}(\tilde{n})}{|1 + \tilde{n}|^2}. \quad (5.3)$$

For skin at 28 GHz with $\varepsilon_r = 16.55$ and $\sigma = 25.8 \text{ S/m}$, $\tilde{n} = 4.49 - 1.79i$ and $T_0 = 0.539$.

5.2.4 Polarization-aware exact absorbed power density

Any incident plane wave is fully polarized, so the exact APD law must be polarization-aware. At a surface point $\mathbf{r}$, decompose the incident electric field into local TE and TM components by projecting on the unit vectors $\hat{e}_s(\mathbf{r}) = \hat{\mathbf{k}} \times \hat{\mathbf{n}} / |\hat{\mathbf{k}} \times \hat{\mathbf{n}}|$ and $\hat{e}_p(\mathbf{r}) = \hat{e}_s \times \hat{\mathbf{k}}$. Let $\mathbf{E}_0 = a_s \hat{e}_s + a_p \hat{e}_p$, with the local TE and TM energy fractions $|e_s|^2 = |a_s|^2 / |\mathbf{E}_0|^2$ and $|e_p|^2 = |a_p|^2 / |\mathbf{E}_0|^2$. The effective transmission at $\mathbf{r}$ is then

$$T_{\text{eff}}(\mathbf{r}) = |e_s(\mathbf{r})|^2 T_s(\theta) + |e_p(\mathbf{r})|^2 T_p(\theta). \quad (5.4)$$

The exact APD at a visible point is therefore

$$\text{APD}(\mathbf{r}) = \text{IPD } T_{\text{eff}}(\mathbf{r}) [\mu(\mathbf{r})]_+. \quad (5.5)$$

Here $[x]_+ = \max(x, 0)$ is the positive part: it keeps the front-facing surface and sets the back-facing surface ($\mu \leq 0$, no incident power) to zero. Equation (5.5) holds for any polarization, any frequency where the body is opaque, and any locally flat surface. The self-shadowing factor $V(\mathbf{r}, \hat{\mathbf{k}})$ of the geometric law in Section 5.2.5 is suppressed in this subsection because the Fresnel calculation operates at a point already taken to be visible. Visibility returns with the multi-source matrix form in Section 5.2.5.6.

To proceed, write

$$T_{\text{eff}}(\mathbf{r}) = T_{\text{avg}}(\theta) + \frac{1}{2} q(\mathbf{r}) \Delta T(\theta), \quad (5.6)$$

with $T_{\text{avg}} = \frac{1}{2}(T_s + T_p)$ the unpolarized baseline, $\Delta T = T_p - T_s$ the polarization splitting, and $q = |e_p|^2 - |e_s|^2 \in [-1, 1]$ the local TM excess. The polarization

correction vanishes pointwise for circularly polarized illumination, in expectation for randomly oriented linearly polarized illumination, and to within 2.5% under multipath averaging with at least 20 paths. First, for circular polarization the TE and TM intensities are equal at every point on every body, so $q \equiv 0$ pointwise. Second, for linear polarization with random ensemble orientation either in space or time, the ensemble average $\langle q \rangle$ vanishes by the same argument. Third, for a body in a multipath environment with N independent path orientations, the standard deviation of the polarization correction scales as $D_B/\sqrt{2N}$, where $D_B \leq 16\%$ is the body's polarization directivity on the Thelonious phantom, and for $N \geq 20$ paths the correction drops below 2.5%. These three conditions follow from the decomposition in (5.6). The last uses the $D_B/\sqrt{2N}$ variance bound. Under any of these conditions the exact law reduces to

$$\text{APD}(\mathbf{r}) = \text{IPD } T_{\text{avg}}(\theta(\mathbf{r})) [\mu(\mathbf{r})]_+ . \quad (5.7)$$

The angular dependence is now confined to the scalar function $T_{\text{avg}}(\theta)$. The next section shows that this function is nearly constant for biological tissue.

5.2.5 Pseudo-Brewster compensation

Pseudo-Brewster compensation makes the unpolarized Fresnel transmission nearly constant for mmWave tissue. As shown in Fig. 5.1, we can then replace the angular Fresnel factor by T_0 to obtain a scalar-weighted geometric law and a simple matrix form for incoherent paths. The later coherent derivation uses the polarization-aware Fresnel law.

5.2.5.1 Mechanism

The Brewster angle of a lossless dielectric is $\theta_B = \arctan(n_2/n_1)$, at which the TM reflection coefficient vanishes [16]. For a lossy dielectric the reflection minimum is finite but small. The angle that minimizes $|r_p|^2$ is the *pseudo-Brewster angle* and satisfies $\theta_{\text{pB}} \approx \arctan |\tilde{n}|$ to within 1° for $|\tilde{n}| > 3$ [17, 18]. At this angle, T_p peaks near 0.95, whereas T_s has fallen below 0.20. Their average $T_{\text{avg}}(\theta_{\text{pB}}) \approx 0.5$ is close to the normal-incidence value $T_0 \approx 0.5$ –0.6 for biological tissue at mmWave.

Azzam [10] showed that for lossless dielectric substrates with refractive index $|\tilde{n}| > 2 + \sqrt{3} \approx 3.73$, the unpolarized reflectance varies by less than 1% over $[0^\circ, 60^\circ]$. Empirically, the near-constancy extends to $|\tilde{n}| > 2.5$, below the strict Azzam threshold. Evaluation on the IT'IS tissue-properties database confirms this extension [19, 20]. Biological tissue in the wireless mmWave band has $|\tilde{n}| \in [3, 6]$, putting it in the high-index regime. This connection between the Azzam criterion and biological dosimetry has not appeared in the antenna propagation or bioelectromagnetics literature. Prior work has evaluated the angular and polarization dependence of body transmission above 6 GHz numerically [21] without the high-index reduction.

Table 5.1: Pseudo-Brewster compensation across tissue types at 28 GHz. The variation column is the maximum deviation of T_{avg}/T_0 from unity over $[0^\circ, 75^\circ]$.

Tissue	ϵ_r	σ [S/m]	$ \tilde{n} $	T_0	T_{avg} var.
Skin	17.0	25.0	4.84	0.54	5.6%
Muscle	25.0	30.0	5.62	0.48	4.8%
Fat	4.0	2.0	2.05	0.77	8.2%
Water	25.0	55.0	6.62	0.45	3.9%

5.2.5.2 Quantitative behavior across angle

Figure 5.3 illustrates the compensation for skin at 28 GHz. Figure 5.3a shows T_s , T_p , and T_{avg} versus incidence angle. Figure 5.3b shows the normalized absorbed power $\text{APD/IPD} = T(\theta) \cos \theta$ for each polarization and for the simplified product $T_0 \cos \theta$. The unpolarized curve closely tracks the simplified prediction, and the small gap is the Fresnel approximation error. T_{avg}/T_0 is at most 1.056 across $[0^\circ, 90^\circ]$ on skin at 28 GHz. Below 20° , the deviation stays below 0.2%.

5.2.5.3 Tissue universality

All biological tissues in the wireless mmWave band cluster in the $|\tilde{n}| > 2.5$ region where the compensation operates. Table 5.1 lists the relevant parameters at 28 GHz from the IT'IS tissue-properties database [19, 20]. Skin and muscle have $|\tilde{n}|$ near 5 and an angular variation below 5.6%. Water has $|\tilde{n}| > 6$ and a variation below 4%. Fat is the outlier in this comparison, with $|\tilde{n}| \approx 2$ and an 8.2% angular variation. Subcutaneous fat lies beneath the skin. Therefore, fat does not determine the air-skin Fresnel interface directly. Subcutaneous fat can still affect net transmission when the field penetrates through the skin. The layered model in Section 5.2.6.3 includes this effect. For superficial exposure of intact skin, the leading interface response depends on the outer skin layers.

5.2.5.4 Frequency dependence

The accuracy of the constant- T_0 approximation has a clean frequency dependence. Define the *sphere ratio* $R(f)$

$$R(f) \equiv T_0(f)/\bar{T}(f), \quad \bar{T}(f) \equiv 2 \int_0^1 T_{\text{avg}}(\mu, f) \mu \, d\mu, \quad (5.8)$$

where $\bar{T}(f)$ is the flux-weighted Fresnel transmission. $R(f) = 1$ when the constant- T_0 approximation is exact on a direction-averaged quantity. $R < 1$ means T_0 underestimates absorbed power. $R > 1$ means it overestimates. Figure 5.4 shows that for skin the crossover is at 40.4 GHz, where the compensation is exact. Below this frequency the approximation underestimates absorbed power. Above, it overestimates by at most 3.5% at 100 GHz. The root-mean-square error remains

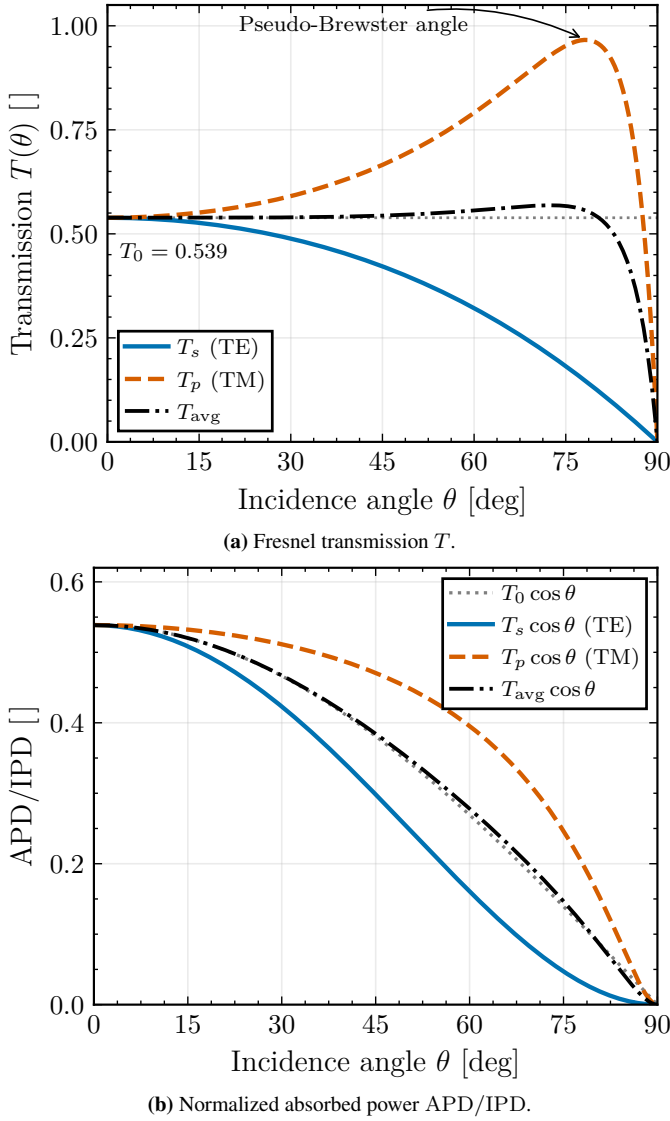


Figure 5.3: Pseudo-Brewster compensation for skin at 28 GHz ($\tilde{n} = 4.49 - 1.79i$, $T_0 = 0.539$). (a) Fresnel power-absorption coefficients T_s (TE), T_p (TM), and $T_{\text{avg}} = \frac{1}{2}(T_s + T_p)$ versus incidence angle θ . T_{avg}/T_0 is at most 1.056 over $[0^\circ, 90^\circ]$. (b) Normalized absorbed power $\text{APD/IPD} = T(\theta) \cos \theta$ for the same three states. The dotted reference is the simplified $T_0 \cos \theta$ prediction.

below 5% across 0.3–100 GHz. The frequency-resolved Cole–Cole values for skin underlie the calculation in Fig. 5.4.

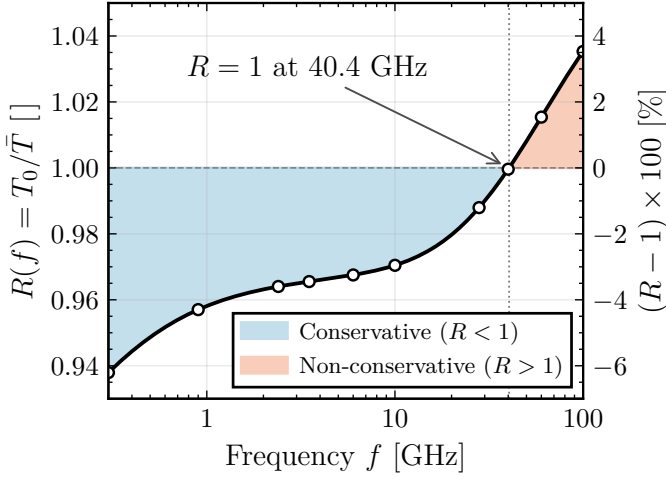


Figure 5.4: Sphere ratio $R(f) = T_0/\bar{T}$ versus frequency for skin (IT'IS tissue-properties database [19, 20]). $R = 1$ indicates that the constant- T_0 approximation is exact on the direction-averaged quantity; $R < 1$ means T_0 underestimates absorbed power and $R > 1$ means it overestimates. The dashed horizontal lines mark the $\pm 4\%$ band.

5.2.5.5 Geometric absorption law

Two simplifications act on the exact law in (5.5). First, the polarization reduction (5.7) removes the polarization dependence. Second, we substitute $T_{\text{avg}}(\theta) \rightarrow T_0$ and reinstate self-shadowing through the binary visibility $V(\mathbf{r}, \hat{\mathbf{k}}) \in \{0, 1\}$. The exact law reduces to the *geometric absorption law*

$$\boxed{\text{APD}(\mathbf{r}) \approx \text{IPD} \cdot T_0 \cdot \left[\hat{\mathbf{n}}(\mathbf{r}) \cdot (-\hat{\mathbf{k}}) \right]_+ \cdot V(\mathbf{r}, \hat{\mathbf{k}})} \quad (5.9)$$

The tissue physics enters through the scalar T_0 . The transmission coefficient T_{tr} fitted in [2, 3, 22] is identified with T_0 , the normal-incidence transmission. All spatial variation depends on the body shape through the surface-normal field $\hat{\mathbf{n}}(\mathbf{r})$ and the visibility field $V(\mathbf{r}, \hat{\mathbf{k}})$. For a convex body, $V \equiv 1$ and (5.9) reduces to the classical convex form $\text{IPD} T_0 \left[\hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}}) \right]_+$. Figure 5.5 shows how visibility enters the geometric law on the Thelonious phantom. Panel (a) shows the frontal APD map. Panels (b) and (c) show the direction-isotropic exposure fraction $\eta(\mathbf{r})$ from the front and side. Under frontal illumination, V drops three regions to zero: the medial thighs, the sides of the torso beneath the arms, and the underside of the jaw.

Hence, the error of (5.9) relative to the exact polarization-aware law is bounded by the maximum of the polarization correction and the angular variation of T_{avg} . The latter is below 5% across the wireless mmWave band (6–100 GHz). The former is below 2.5% for $N \geq 20$ independent multipath components, and at most

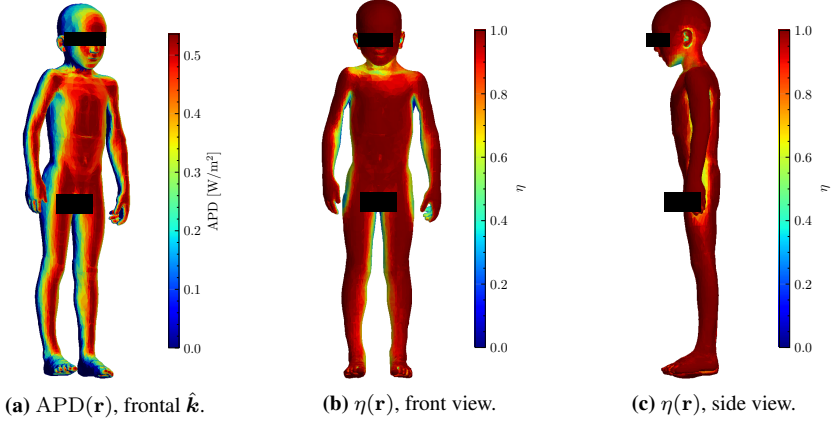


Figure 5.5: APD and η maps on the Thelonious phantom (skin at 28 GHz, $\text{IPD} = 1 \text{ W/m}^2$, area-weighted mean $\bar{\eta} = 0.865$). (a) APD under frontal illumination $\hat{\mathbf{k}} = +\hat{\mathbf{y}}$. Front-facing triangles absorb at the cosine rate $T_0 \text{IPD} \cos \theta$. Self-shadowed elements drop to zero through $V(\mathbf{r}, \hat{\mathbf{k}})$. (b, c) Direction-isotropic exposure fraction $\eta(\mathbf{r}) \in [0, 1]$ from (5.11), front and side views. Panel (a) is the integrand of the Cauchy formula along one direction. Panels (b, c) integrate over the full sphere.

16% on a real human body for the worst-case linearly polarized single plane wave. The combined error is below the 20% uncertainty in tissue dielectric properties at mmWave [23].

5.2.5.6 Discrete multi-source form

Equation (5.9) extends to a triangle mesh under multiple incident waves. Discretize the body into M_Σ triangles. Row j of $\mathbf{N} \in \mathbb{R}^{M_\Sigma \times 3}$ holds the outward unit normal $\hat{\mathbf{n}}_j$. Let N plane waves arrive with unit directions $\hat{\mathbf{k}}_1, \dots, \hat{\mathbf{k}}_N$ and incident power densities $\text{IPD}_1, \dots, \text{IPD}_N$. Stack the directions column-wise into $\mathbf{K} \in \mathbb{R}^{3 \times N}$, with column i equal to $-\hat{\mathbf{k}}_i$. Stack the incident power densities into $\mathbf{IPD} = [\text{IPD}_1, \dots, \text{IPD}_N]^\top \in \mathbb{R}^N$. Let $\mathbf{V} \in \{0, 1\}^{M_\Sigma \times N}$ be the visibility matrix, with $V_{ji} = 1$ when direction $\hat{\mathbf{k}}_i$ reaches triangle j , and $V_{ji} = 0$ otherwise. Collect the per-triangle APD values into $\mathbf{APD} \in \mathbb{R}^{M_\Sigma}$.

The geometric law on the mesh then reads

$$\mathbf{APD} = T_0 ([\mathbf{N} \mathbf{K}]_+ \odot \mathbf{V}) \mathbf{IPD}. \quad (5.10)$$

The cosine matrix $\mathbf{N} \mathbf{K} \in \mathbb{R}^{M_\Sigma \times N}$ has entry (j, i) equal to $\hat{\mathbf{n}}_j \cdot (-\hat{\mathbf{k}}_i)$. The operator $[\cdot]_+ \equiv \max(\cdot, 0)$ acts componentwise, and clamps back-facing entries to zero. The Hadamard product $\odot$ with $\mathbf{V}$ gates self-shadowed entries. The product with $\mathbf{IPD}$ sums the contributions of the N incident waves.

Each step is differentiable almost everywhere. The operator $[\cdot]_+$ is the rectified linear unit (ReLU). Replacing it with the smooth Gaussian error linear unit (GELU) activation [24] leaves the structure intact and replaces the hard cutoff with a soft rolloff (Eq. (5.16)). Gradients of regulatory quantities with respect to antenna positions, antenna orientations, and RIS phases propagate through any differentiable ray tracer [25]. Binary visibility changes discontinuously at occlusion boundaries, so geometry gradients apply within regions of unchanged visibility and ray paths. The arithmetic primitive is the per-pixel shading operation that consumer GPUs run at sub-millisecond rates, with the cosine gate as rectified shading and $\mathbf{V}$ as ambient occlusion. For $M_\Sigma \approx 10^4$ and $N \approx 10^2$, the spatial map is one matrix-vector multiply on the GPU.

5.2.6 Whole-body absorbed power

Next, as shown in the flowchart (Fig. 5.1), this section turns surface APD into direction-averaged whole-body absorbed power. The needed new ingredient is visibility: nonconvex body parts can shadow one another.

5.2.6.1 Self-shadowing and ambient occlusion

The human body is not convex. Concavities, e.g., the armpits, the gap between the legs, and the neck region, cause one part of the body to shadow another. The binary visibility $V(\mathbf{r}, \hat{\mathbf{k}}) \in \{0, 1\}$ in (5.9) is the ambient-occlusion primitive of computer graphics that Zhukov *et al.* [12] introduced and Landis [13] brought into production rendering. Modern GPUs evaluate $V(\mathbf{r}, \hat{\mathbf{k}})$ as a standard ambient-occlusion pass [14]. The *exposure fraction* η at a surface point $\mathbf{r}$ is the cosine-weighted fraction of the upper hemisphere from which $\mathbf{r}$ is unobstructed,

$$\eta(\mathbf{r}) = \frac{1}{\pi} \int_{S^2} \left[\hat{\mathbf{n}}(\mathbf{r}) \cdot (-\hat{\mathbf{k}}) \right]_+ V(\mathbf{r}, \hat{\mathbf{k}}) d\Omega. \quad (5.11)$$

For convex bodies $V \equiv 1$ and $\eta \equiv 1$. For nonconvex bodies $\eta \in [0, 1]$.

The exposure fraction η is mathematically identical to the self-shadowing factor γ_s that Flintoft *et al.* define as “the proportion of total surface area of the body that is illuminated by the reverberant field” [7, p. 3301] and estimate geometrically as 0.75–0.85 from Tomita’s surface-area data [26]. The Flintoft estimate is geometric and posture-dependent. The construction here is computational and posture-resolved. For the Thelonious phantom, an ambient-occlusion solver returns the area-weighted mean $\bar{\eta} = A_{ab}/A = 0.865$. This is near the upper end of Flintoft’s band $[0.75, 0.85]$ [7]. Figure 5.5(b) and (c) render it on the phantom. Most of the body has $\eta \approx 1$. Reductions occur in concavities. The medial sides of the legs and arms, the armpits, and the underside of the jaw are the dominant such regions. Because η depends only on body shape, the solver precomputes it once per posture.

5.2.6.2 Generalized Cauchy formula

The generalized Cauchy formula is the central whole-body identity. Let a body Σ have surface area A , exposure fraction $\eta(\mathbf{r})$, and absorption area $A_{\text{ab}} \equiv \int_{\Sigma} \eta(\mathbf{r}) \, dA$. Under isotropic, unpolarized plane-wave illumination of intensity IPD on tissue with normal-incidence transmission T_0 , the direction-averaged whole-body absorbed power is

$$\langle P_{\text{abs}} \rangle = \text{IPD } T_0 A_{\text{ab}}/4. \quad (5.12)$$

To see why, apply Fubini's theorem to exchange the surface and direction integrals. The local law (5.9) gives $\text{APD}(\mathbf{r}, \hat{\mathbf{k}}) = \text{IPD } T_0 V(\mathbf{r}, \hat{\mathbf{k}}) \left[\hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}}) \right]_+$. The direction average of the integrand is

$$\frac{1}{4\pi} \int_{S^2} \text{IPD } T_0 V(\mathbf{r}, \hat{\mathbf{k}}) \left[\hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}}) \right]_+ \, d\Omega = \frac{\text{IPD } T_0}{4} \eta(\mathbf{r}),$$

using the definition of η and the identity $\int_{S^2} \left[\hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}}) \right]_+ \, d\Omega = \pi$ for any unit $\hat{\mathbf{n}}$. Integration over Σ gives (5.12).

The classical Cauchy formula from 1841 [11], $\langle A_{\perp} \rangle = A/4$, is the special case $\eta \equiv 1$, valid for any convex body. The absorption area A_{ab} reduces all geometric complexity of self-shadowing to a single scalar. Let A_{CH} be the surface area of the convex hull of the body. Energy conservation under isotropic illumination implies $\langle P_{\text{abs}} \rangle \leq \text{IPD } A_{\text{CH}}/4$, because the power entering the convex hull bounds the absorbed power. For the Thelonious phantom $A_{\text{CH}}/A \approx 1.20$, so the hull bound brackets the true absorbed power within that factor.

The constant- T_0 approximation in (5.12) is accurate to 5% root-mean-square across 0.3–100 GHz. Using the angular average $\bar{T}$ gives

$$\langle P_{\text{abs}} \rangle = \text{IPD } \bar{T}(f) A_{\text{ab}}/4. \quad (5.13)$$

Within the local planar model, this direction-averaged expression is exact for an opaque convex body with spatially uniform tissue properties under isotropic illumination. For a nonconvex anatomical body, we use the equality as engineering shorthand for the factorization of angular transmission and geometrical visibility. The accuracy of this expression also depends on local planarity and the treatment of shadowing and finite-size effects. Table 5.2 lists T_0 , $\bar{T}$, and the ratio $R = T_0/\bar{T}$ for skin from 0.3–100 GHz.

The reverberation-chamber literature has been measuring $\bar{T}$ directly. Bamba's empirical efficiency $\eta(f)$ coincides with $\bar{T}(f)$ to 3% at 5.8 GHz on four FDTD ellipsoid phantoms under diffuse-field exposure [6]. It diverges below 3 GHz, where the Mie contribution to absorption on a finite ellipsoid becomes non-negligible (Table 5.8). The framework is mainly a mmWave method. Flintoft's plateau $\langle Q^a \rangle / \gamma_s = 0.47\text{--}0.49$ at 7–11 GHz matches $\bar{T}$ at the same frequencies to 2% [7]. Zhang's plateau $\xi = 0.45\text{--}0.65$ above 6 GHz brackets $\bar{T} \cdot A_{\text{ab}}/A$ [8].

Table 5.2: Normal-incidence transmission T_0 , flux-weighted transmission $\bar{T}$, and their ratio $R = T_0/\bar{T}$ for skin (IT'IS tissue-properties database [19, 20]).

f [GHz]	$ \tilde{n} $	T_0	$\bar{T}$	R
0.3	7.93	0.381	0.406	0.938
0.9	6.70	0.445	0.465	0.957
2.4	6.29	0.470	0.488	0.964
6.0	6.07	0.481	0.497	0.968
10	5.87	0.489	0.504	0.971
28	4.84	0.536	0.543	0.988
40	4.30	0.570	0.571	1.000
60	3.68	0.622	0.613	1.015
100	3.01	0.701	0.677	1.035

5.2.6.3 Layered transmission below 6 GHz

Above 6 GHz, (5.13) matches the plateau values reported by Bamba, Flintoft, and Zhang. Below 6 GHz, Flintoft and Zhang observe a structured dip near 3 GHz that the homogeneous half-space model does not reproduce [7, 8]. The dip is anatomical. Flintoft's data show $\langle Q^a \rangle$ correlating negatively with mean subcutaneous fat thickness d_{SF} , steepest at 3 GHz (-0.0061 mm^{-1} , $R^2 = 0.40$, [7, Table 6]), with the slope falling to -0.0030 mm^{-1} at 7–11 GHz.

The mechanism is a Fabry–Pérot resonance in the subcutaneous fat layer. Below 6 GHz the SAR penetration depth in fat exceeds 70 mm, against fat thicknesses of 2–20 mm in the Flintoft cohort [7, Table 1]. The wave passes through the fat layer with little attenuation and reflects from the fat-muscle interface. Constructive interference enhances absorption, and destructive interference suppresses it. A three-layer transfer-matrix model gives the layered transmission, stacking skin, fat, and a semi-infinite muscle half-space,

$$T_{\text{lay}}(f, d_{\text{SF}}) = 1 - \left| \tilde{\Gamma}_1(f, d_{\text{SF}}) \right|^2, \quad (5.14)$$

where $\tilde{\Gamma}_1$ is the generalized Fresnel reflection coefficient at the air-skin interface, computed recursively from the fat-muscle interface upward [16, 27]. The generalized coefficient follows from the Chew recursion, and the standing-wave SAR can then be integrated layer by layer. Replacing $\bar{T}$ with T_{lay} in (5.13) gives a frequency-dependent direction-averaged absorbed power that includes the fat-layer resonance. For a fat thickness of 10 mm the model predicts a 40% enhancement above the homogeneous prediction at 0.9 GHz (quarter-wave matching) and a 27% reduction at 3.5 GHz (destructive interference).

Zhang derives the planar limit of this model in his thesis [8, Sec. 2.2] and observes the resonance shift with fat thickness in his Figs. 2.7–2.8, writing that “the fat layer may act as a matching layer between skin and muscle” [8, p. 21]. The contribution here is to embed the planar model in the body-surface integral via T_{lay} and

(5.13), which makes the resonance compatible with a Cauchy-style direction average. Body-surface averaging suppresses the oscillation by a factor of approximately $A_{\text{exposed,fat}}/A$ because different body regions carry different fat thicknesses, with limbs near 2 mm and abdomen near 30 mm, and consequently different resonance frequencies. The integrated dip is shallower than the single-thickness prediction but is at the same frequency. The local surface map $\text{APD}(\mathbf{r}) \approx \text{IPD } T_0 V [\mu]_+$ loses pointwise meaning below 6 GHz, where penetration into deeper tissue becomes important. The layered coefficient T_{lay} includes reflections within the chosen planar stack. We assume local planarity and neglect lateral transport and finite-body scattering when using T_{lay} for total body absorption. Therefore, inward surface flux and local volumetric SAR describe different quantities.

5.3 Validation and error analysis

The theory is validated in four independent ways: (i) Mie theory on lossy spheres, (ii) full polarization-aware Fresnel calculations on the Thelonious phantom, (iii) Sim4Life FDTD on the same phantom, and (iv) the reverberation-chamber and FDTD literature across 108 volunteers and 5 phantoms. The four checks isolate, respectively, the Fresnel approximation, realistic anatomy, volumetric FDTD agreement, and population-level scaling. We then add the higher-order corrections for curvature, diffraction, and inter-body reflection, and close with an error budget bounded by the dielectric uncertainty.

5.3.1 Setup

Thelonious is a 6-year-old male phantom from the Virtual Population [19], shown in Fig. 5.5. A small child phantom is the worst case for the surface law: diffraction is more prominent on smaller body parts at a given frequency, so agreement here generalizes favorably to larger adults. The surface is a high-resolution triangle mesh with 23,826 faces. Tissue properties at every frequency follow the tissue-properties database [19, 20]. Mie benchmarks use lossy spheres of skin permittivity at the listed frequencies, evaluated with the standard recursive series of Bohren and Huffman [28]. Sim4Life FDTD runs use the 0.45–5.8 GHz band on the same Thelonious mesh embedded in a free-space cube with a perfectly matched layer of 10 cells, voxel edge of 1 mm in the body and graded 1–4 mm outside, and 12 plane-wave directions per frequency at two orthogonal polarizations. Path-level data come from a differentiable ray-tracer [25] with no roughness model. The companion code release contains all scripts and input geometries that produced the figures in this section.

5.3.2 Mie theory on lossy spheres

The Mie series gives an exact solution for the absorption efficiency Q_{abs} of a lossy sphere of radius a and complex refractive index $\tilde{n}$. The geometric law predicts

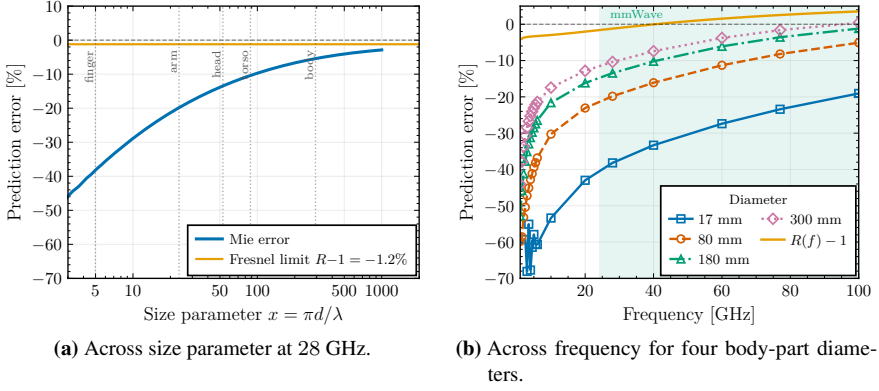


Figure 5.6: Mie validation against lossy spheres with frequency-dependent IT'IS skin properties [19, 20]. (a) Prediction error versus size parameter at 28 GHz. Vertical dashed lines mark body-part sizes. The curve converges from below to the Fresnel limit $R - 1 \approx -1.2\%$ as $x \rightarrow \infty$. (b) Prediction error versus frequency for finger (17 mm), arm (80 mm), head (180 mm), and torso (300 mm) diameters. The wireless mmWave band is shaded green. The orange asymptote is $R(f) - 1$, the size-independent Fresnel limit.

$P_{\text{abs}} = \text{IPD } T_0 \pi a^2$, so its error is $(T_0/Q_{\text{abs}} - 1)$. Skin properties come from the IT'IS database [19, 20] at each frequency. The total error splits into two contributions. The Fresnel approximation error is shape- and frequency-dependent but size-independent. On a sphere it is the sphere ratio $R = T_0/\langle T_{\text{avg}} \rangle$, which crosses unity at approximately 39 GHz (Fig. 5.4). The diffraction error is size-dependent and scales as $x^{-2/3}$ in the optical regime, where $x = \pi d/\lambda$ is the size parameter. Diffraction bends waves into the geometric shadow, adding absorption that the surface law misses. We refer to the regime where x is small enough that this diffracted contribution exceeds a few percent of total absorption as the Mie regime. For body-scale targets it corresponds to frequencies below approximately 6 GHz.

Figure 5.6 shows the Mie validation. Figure 5.6(a) gives the error versus size parameter at 28 GHz, converging from below to the Fresnel limit $R - 1 \approx -1.2\%$ as $x \rightarrow \infty$. Figure 5.6(b) gives the error versus frequency for four representative body-part diameters. For body-relevant sizes (head, torso) over 6–100 GHz, the error ranges from 0.4% on a torso at 100 GHz to 14% on a head at 28 GHz, set mostly by diffraction into the geometric shadow at the low end of the band. At 28 GHz the law underestimates absorption. For fingers below 6 GHz, errors exceed 30%. On body-scale objects in the claimed regime, the residual stays within the dielectric uncertainty on T_0 (Fig. 5.9).

Table 5.3: Geometric law versus full Fresnel integration on the Thelonious phantom (skin at 28 GHz, plane wave from above).

Metric	Simplified	Full Fresnel	Error
Mean APD (illum.)	0.185 W/m ²	0.186 W/m ²	0.5%
Peak APD	0.539 W/m ²	0.539 W/m ²	0.0%

5.3.3 Full Fresnel on the Thelonious phantom

The Mie test bounds the Fresnel error on a smooth shape. This subsection validates the theory on a realistic human body. We compare the simplified prediction $\text{APD}^{\text{simpl}} = \text{IPD } T_0 [\mu]_+$ against the full polarization-aware Fresnel integration $\text{APD}^{\text{full}} = \text{IPD } T_{\text{eff}}(\theta, \text{pol}) [\mu]_+$ on the Thelonious mesh (23 826 triangles, 0.787 m² surface area). The incident plane wave impinges from above. The computation is done at 28 GHz.

Table 5.3 reports the pointwise comparison. For the 4 907 illuminated triangles with $\theta < 75^\circ$, the local statistics are mean error -2.6% , root-mean-square 3.2% , and range $[-5.3\%, 0.0\%]$. The peak APD is recovered exactly because the maximum is at normal incidence, where $T_{\text{eff}}(0) = T_0$ regardless of polarization. The local error is below 5.5% everywhere with $\theta < 75^\circ$. Above 75° the local error rises, but these surfaces carry only 15% of the absorbed power. A sweep over 128 illumination directions and three polarization states extends the analysis beyond the pointwise comparison. The per-direction distribution of total absorbed power clusters around $T_0 A_\perp$ within the directional spread set by self-shadowing.

5.3.4 Sim4Life FDTD on the Thelonious phantom

The Mie and Fresnel tests check approximations against analytic and semi-analytic ground truths. Full Sim4Life FDTD on the same Thelonious mesh, matched dielectric properties, and matched plane-wave excitation completes the comparison. These simulations are the Thelonious subset of the four-phantom FDTD campaign described in Chapter 2. The comparison evaluates two regulatory metrics. The first is the IEC/IEEE 63195 peak APD averaged over a 4 cm² patch. The direction-averaged ratio of law to FDTD is 1.027 at 7 GHz over three lateral and frontal incidence directions with θ -polarization. A $\pm 20\%$ uncertainty on the IT'IS dielectric properties [19, 20] propagates through the Fresnel coefficient at 7 GHz to $\pm 7\%$ on T_0 , and the 1.027 average sits inside this band. The per-direction values 1.06, 1.20, and 0.83 scatter by about $\pm 15\%$, but that scatter is FDTD reference noise, not closed-form error, and cancels on averaging.

The second metric is the direction-averaged Cauchy formula (5.13) across 12 directions and 2 polarizations at 5.8 GHz. The ratio of law to FDTD on direction-averaged total absorbed power is 1.012, with $A_{\text{ab}}/A = 0.865$ and $\bar{T}(f)$ from Table 5.2. Figure 5.7 extends the comparison across 0.45–5.8 GHz. The closed-form Cauchy prediction approaches unity at the upper end of the band. Below 6 GHz the

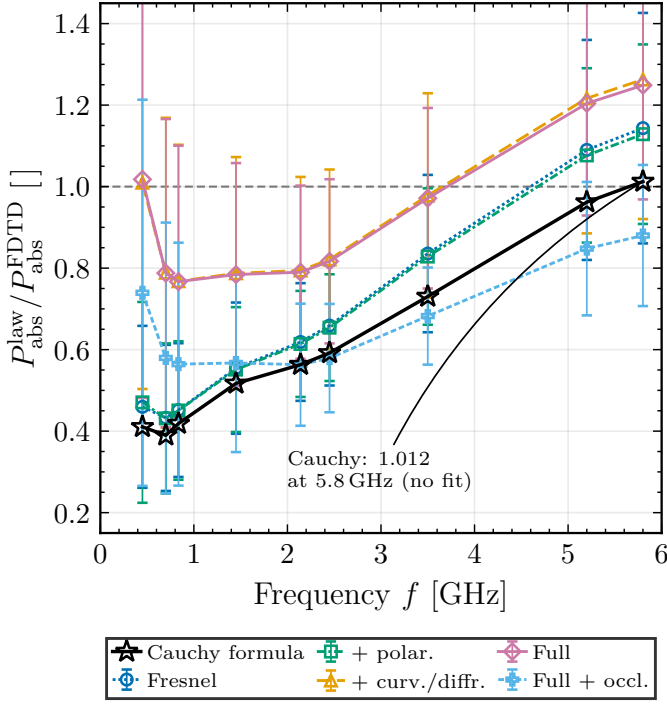


Figure 5.7: Closed-form prediction versus Sim4Life FDTD on the Thelonious phantom. Twelve directions and two polarizations per frequency from 0.45–5.8 GHz. Error bars show the spread across directions. The kernel curves switch on the corrections of Section 5.3.6 in sequence: “Fresnel only” uses T_s/T_p at the convex limit, “+ polarization” adds the polarization-aware T_{eff} , “+ curvature & diffraction” adds the $1/(kR)$ refinement, “Full kernel” is the constant- T_0 geometric law without occlusion, “Full + occlusion” multiplies by $V(\mathbf{r}, \hat{\mathbf{k}})$. The Cauchy stars are the closed-form whole-body identity, giving 1.012 at 5.8 GHz. The layered T_{lay} of Section 5.2.6.3 recovers the sub-6 GHz dip qualitatively.

surface law underestimates because body-scale Mie and resonance effects do not enter a surface-only law, in line with the Mie analysis on a sphere of comparable size parameter.

5.3.5 Combined dosimetry literature

The literature comparison maps each reported empirical scalar to the corresponding closed-form quantity. Kodera’s transmission coefficient T_{tr} is compared with the Fresnel transmission used in the one-dimensional reference model. Flintoft’s self-shadowing factor γ_s is compared with the surface mean of the exposure fraction $\eta(\mathbf{r})$. Bamba’s efficiency $\eta(f)$ and Zhang’s coefficient ξ are compared with the whole-body factor $\bar{T}(f)A_{\text{ab}}/A$. The plotted Flintoft points are linear-regression

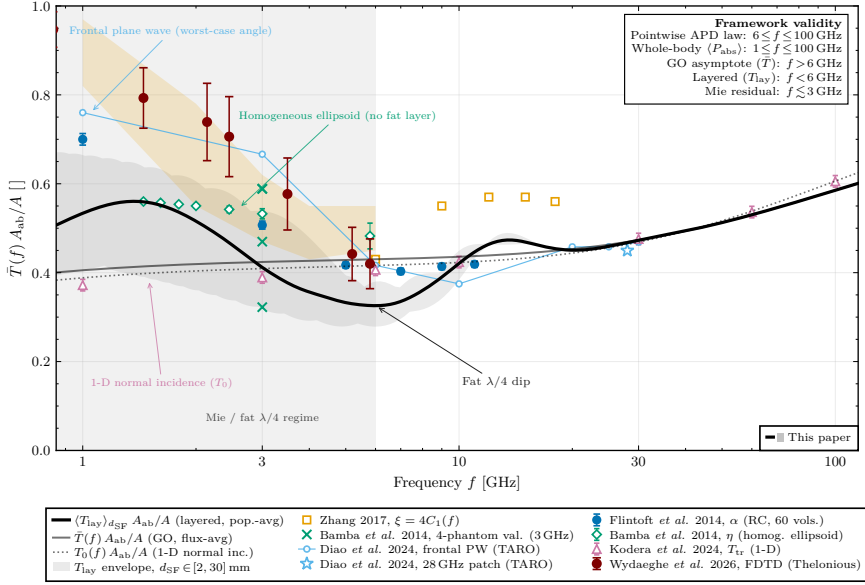


Figure 5.8: Closed-form prediction (5.13) compared with direction-averaged whole-body absorption ratios from the dosimetry literature. The thick black line uses the population-averaged layered transmission, the thin black line is the geometric-optics asymptote $\bar{T}(f)A_{ab}/A$, and the dotted line is the normal-incidence reference $T_0(f)A_{ab}/A$. The gray band shows the layered-transmission envelope for subcutaneous-fat thicknesses $d_{SF} \in [2, 30]$ mm. Error bars are standard errors of the mean. The inset gives framework validity by frequency band.

intercepts of $\langle Q^a \rangle$ at $d_{SF} = 0$ with $\gamma_s = 1$ [7, Eq. 6]. The plotted Zhang points combine the 6–18 GHz plateau from [8, Fig. 4.9] with the 1–6 GHz envelope from [8, Fig. 4.11]. Figure 5.8 then compares the closed-form prediction (5.13) against 108 volunteers and 5 FDTD phantoms from 1 to 100 GHz.

Table 5.4 lists the numerical comparisons. Bamba *et al.* [6]’s η in panel (c) is fit from full-body FDTD on ellipsoidal phantoms in diffuse-field exposure. Their fit absorbs creeping-wave and finite-curvature contributions that the planar-tissue $\bar{T}$ omits. At 5.8 GHz, the upper edge of their calibration range, η converges to $\bar{T}$ in the geometric-optics regime predicted by a Mie analysis of body-scale spheres [28]. The 1.45–3 GHz portion of their fit lies outside the geometric-optics validity window of the present framework (Table 5.8). The systematic divergence in panel (c) below 3 GHz is the Mie regime, not a model failure. Bamba *et al.*’s anatomical-phantom validation at 3 GHz returns residuals of -39.4% , -11.7% , $+10.7\%$, and $+10.6\%$ on the Thelonious, Billie, Ella, and Duke phantoms [6, Table 7]. The largest divergence is on the smallest phantom. The same mechanism appears in panel (d) on the Diao *et al.* [3] TARO sweep (frontal plane wave, vertical polarization, projected area 0.54 m^2), where T_{eff} rises from 0.43 at 10 GHz to 0.88

Table 5.4: Quantitative comparison of the closed-form prediction to the empirical literature. The shaded sub-3 GHz regime, where the layered tissue model in Section 5.2.6.3 replaces $\bar{T}$, is excluded.

Reference	Empirical observation	Closed-form prediction	Match
Flintoft [7]	$\langle Q^a \rangle / \gamma_s = 0.47\text{--}0.49$ at 7–11 GHz, 60 volunteers	$T_0(f) = 0.48$ at 9 GHz, $\bar{T}(f) = 0.50$	2%–4%
Bamba [6]	$\eta(f) = 0.48\text{--}0.56$ at 1.45–5.8 GHz, four FDTD ellipsoids	$\bar{T}(f) = 0.47\text{--}0.50$	3% at 5.8 GHz, convergent with frequency
Zhang [8]	$\xi = 0.45\text{--}0.65$ at 6–18 GHz, 48 subjects	$\bar{T}(f) \cdot A_{\text{ab}}/A = 0.43\text{--}0.49$	within scatter
Kodera [2]	T_{tr} matches $A_{\perp}$ scaling at 10–100 GHz, parametric FDTD	$T_{\text{tr}} \equiv T_0$	$\leq 5\%$
Diao [3]	$T = 0.52$ at 28 GHz, anatomical FDTD	$T_0 = 0.536$ at 28 GHz	3%
Flintoft [7]	-0.0061 mm^{-1} slope of $\langle Q^a \rangle$ vs d_{SF} at 3 GHz	Layered Fabry–Pérot in fat	mechanism, qualitative

at 1 GHz.

Kodera *et al.* [2] report the closest numerical counterpart to the present analysis. Their Fig. 13 compiles whole-body absorbed SAR data over 1–10 GHz at IPD = 10 W/m^2 across nine prior numerical phantom studies and two reverberation-chamber measurement campaigns. Their Fig. 6 extends the same comparison to 1–100 GHz on five parametric layered models (Models I–V). The compilation shows the asymptotic plateau that (5.13) predicts. Kodera *et al.* fit a study-specific T_{tr} per phantom and frequency from a one-dimensional multilayer slab calculation. Their homogeneous-skin curve (Fig. 9, right axis) reproduces the Fresnel T_0 within 1–2% above 6 GHz, and oscillates around that value below 6 GHz with a multilayer Fabry–Pérot pattern of the same form as the layered transmission T_{lay} in Section 5.2.6.3. Equation (5.13) supplies the closed-form $T_{\text{tr}} \rightarrow \bar{T}(f)$ that all phantoms converge to in the geometric-optics regime. The residual phantom-to-phantom spread is set by the body-shape factor A_{ab}/A .

5.3.6 Higher-order corrections

The correction box in the flowchart collects the effects left out by the geometric law. We examine three types of corrections: curvature, diffraction at the shadow boundary, and inter-body reflections. The labels in Fig. 5.7 (“Fresnel only,” “+ polarization,” “+ curvature & diffraction,” “Full kernel,” “+ occlusion”) switch each correction on against the same FDTD reference.

First, consider the influence of curvature. The first-order Physical Optics correction multiplies the geometric law by $1 + \mu/(kR_1) + \mu/(kR_2)$ for a surface

Table 5.5: Curvature correction at 28 GHz ($k \approx 587 \text{ m}^{-1}$). The correction is below the Fresnel approximation error for most body regions and concentrates at small features.

Region	R [mm]	$1/(kR)$	Correction
Torso, head	> 100	$< 0.2\%$	negligible
Arm	approx. 40	0.4%	approx. 0.4%
Finger	approx. 8	2.1%	approx. 2%
Ear edge	approx. 2	8.5%	approx. 8%

with twice the local mean curvature $H = 1/R_1 + 1/R_2$, where $k = 2\pi/\lambda$ is the free-space wavenumber. Since $[\mu]_+ \cdot \mu = [\mu]_+^2$, the per-triangle update separates additively,

$$\text{APD}^{(j)} = T_0 \sum_i S_i \left[[\mu_{ji}]_+ + \frac{H_j}{k} [\mu_{ji}]_+^2 \right] V_{ji}, \quad (5.15)$$

adding a quadratic gate on top of the linear one.

Here, $S_i = \text{IPD}_i$ is the incident power density of path i , $\mu_{ji} = \hat{\mathbf{n}}_j \cdot (-\hat{\mathbf{k}}_i)$, and $H_j = 1/R_{1,j} + 1/R_{2,j}$ is twice the mean curvature of triangle j . The magnitude is set by $1/(kR)$. Table 5.5 lists the correction at 28 GHz on representative body parts. The correction grows as the wavelength approaches the local body-part size. At sub-6 GHz frequencies, the smallest features have $kR \lesssim 5$ where the correction is no longer small. At 28 GHz, only the ear edges and fingertips carry a correction above the Fresnel error floor.

Second, we quantify the effect of diffraction at the shadow boundary. The sharp $[\cdot]_+$ cutoff at $\mu = 0$ is a geometric-optics idealization. Diffraction smooths the shadow edge over a Fresnel-zone width $\sqrt{\lambda R_j}$. The physical activation becomes

$$\mu \mapsto \mu \frac{1}{2} [1 + \text{erf}(\mu/\sigma_j)], \quad \sigma_j = \sqrt{\lambda/(2\pi R_j)}. \quad (5.16)$$

The ICNIRP centimeter-scale spatial averaging regularizes the boundary at a length scale larger than σ_j across the wireless band, so the diffraction correction is significant only for high-resolution local maps or for comparisons against point measurements. On the Thelonious phantom, the integrated whole-body effect is 1.2% at 28 GHz, below 1% above 30 GHz, and several percent below 6 GHz, in line with the Mie analysis on body-scale spheres in Section 5.3.2. Finally, we study the impact of inter-body reflections. At a surface point the fraction T_0 is absorbed and the remaining $1 - T_0 \approx 0.46$ is reflected. On a nonconvex body, part of this reflected power re-illuminates another point and contributes to absorption that the first-bounce law omits. The radiosity series gives a multiplier $C(\mathbf{r}) = 1/(1 - \bar{R} f(\mathbf{r}))$ at each point, where $\bar{R} = 1 - \bar{T} \approx 0.46$ is the flux-weighted reflectance and $f(\mathbf{r}) \leq 1 - \eta(\mathbf{r})$ is the recapture fraction bounded by the local nonvisible hemisphere area. Two effects keep the body-averaged correction small. First, the bound $f \leq 1 - \eta$ self-compensates: deep concavities (η low) have a high recapture fraction (f high),

so the product $\eta \cdot C$ varies much less than η alone. Second, specular reflection at mmWave (skin meets the Rayleigh roughness criterion) reduces f by roughly a factor of three relative to the diffuse bound. On the Thelonious phantom at 28 GHz, the area-weighted recapture fraction is $f_{\text{global}} \approx 0.09$ under the diffuse bound, giving $C \approx 1.04$. The specular estimate gives $C \approx 1.01$. The body-averaged correction stays below 2%, smaller than the propagated dielectric uncertainty derived in Section 5.3.7.

5.3.7 Error budget

Figure 5.9 reports two regimes side by side at 28 GHz on skin. The worst case is single body part, single direction, pointwise local. The typical case is whole-body integrated, direction-averaged. The dielectric input spread is $\pm 20\%$ on ϵ_r and σ . This is the inter-model gap between Gabriel *et al.* [20] and the empirical Gabriel-times-1.2 fit that Christ *et al.* [29] obtained from S_{11} measurements on 37 volunteers at 40–110 GHz. The spread is consistent with mmWave dielectric campaigns more broadly [23, 30, 31]. Evaluating $T_0 = 4n/[(1+n)^2 + \kappa^2]$ at the four corners of the $\pm 20\%$ box gives the largest skin deviation of $\pm 7\%$ at 28 GHz. The Fresnel approximation worst case is 5.3% pointwise local (Table 5.3). The typical case is 1.2% direction-averaged on whole-body absorbed power in the 128-direction sweep. The diffraction worst case is 10% on a torso-scale Mie sphere (Section 5.3.2). The typical case is 1.2% when integrated on Thelonious. The inter-body reflection worst case is 4% under the diffuse bound. The typical case is 1% under specular at mmWave (Section 5.3.6). In the typical case every model error stays below the dielectric uncertainty.

5.4 Compliance bounds

Within the surface-model assumptions, bounds on the ICNIRP basic restrictions follow in closed form from the incident power density. Section 5.4.1 bounds the incident power density allowed for whole-body SAR. Section 5.4.2 bounds the peak spatial-average SAR over a 10 g cube.

5.4.1 Whole-body SAR threshold

The ICNIRP 2020 guidelines [1] specify a whole-body average SAR limit of 0.08 W/kg for the general public. In the constant-transmission geometric model, the bound $A_{\perp}(\hat{\mathbf{k}}) \leq A/2$ gives $\text{SAR}_{\text{wb}} \leq \text{IPD} \bar{T} A / (2m)$. Therefore, the following expression is a sufficient incident-power threshold within that model. The angular mean transmission $\bar{T}$ is an approximation and can be lower than the transmission for an individual direction and polarization.

$$\text{IPD}_{\text{max}} = \frac{0.16 m}{\bar{T} A}, \quad (5.17)$$

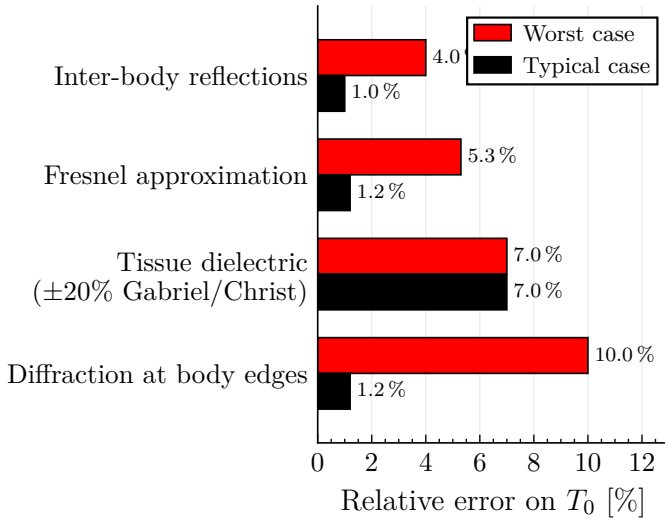


Figure 5.9: Error budget for the geometric law in two regimes at 28 GHz on skin. Worst case is single body part, single direction, pointwise. Typical case is whole-body integrated, direction-averaged. Only the dielectric uncertainty stays large in the typical case.

a closed-form function of body mass m , body surface area A , and tissue transmission $\bar{T}$, none of which requires an FDTD solve on the specific exposure scenario.

The body surface area follows the Du Bois formula [32],

$$A \approx 0.007184 m^{0.425} h^{0.725}, \quad (5.18)$$

with mass in kg and height in cm. Therefore, $\text{IPD}_{\max}$ scales as $m/A \propto \text{BMI}^{0.575} h^{0.425}$. Table 5.6 evaluates (5.17) on a representative population at 28 GHz with $\bar{T} = 0.543$. The scaling matches the observation in the dosimetry literature [33, 34] that absorption cross-section scales with surface area, whereas mass scales with volume. The body polarization directivity bounds the linearly polarized worst-case correction to (5.17). Section 5.5.2 states the implications for the existing ICNIRP general-public reference level above 6 GHz.

5.4.2 Peak spatial-average SAR over a 10 g cube

Below 6 GHz the ICNIRP basic restriction is the peak spatial-average SAR over a 10 g cube [1, 35]. An energy-conservation argument on the cube footprint bounds this restriction by the absorbed power density, so no explicit cube search is needed.

The following bound links the cube quantity to APD. For an axis-aligned 10 g cube placed per IEC/IEEE 62704-1 on a planar three-layer body, the peak

Table 5.6: Sufficient whole-body SAR thresholds for representative body sizes in the constant-transmission geometric model at 28 GHz, with $\bar{T} = 0.543$. A value below the reference level leaves the actual whole-body SAR at that level unresolved. The infant surface-area estimate uses the same anthropometric approximation as the other rows.

Body type	m [kg]	h [cm]	$\text{IPD}_{\max}$ [W/m ²]
Infant (1 yr)	8	70	6.2
Child (6 yr)	20	110	7.6
Adolescent	50	160	9.9
Adult (ref.)	70	170	11.4
Large adult	100	180	13.5

spatial-average SAR satisfies

$$\text{psSAR}_{10\text{g}} \leq \frac{\sqrt{2} \langle \text{APD} \rangle_{1/4\text{cm}^2}}{\rho_m L}, \quad (5.19)$$

where $L = (m/\rho_m)^{1/3} = 21.5$ mm and $\langle \text{APD} \rangle_{1/4\text{cm}^2}$ is the local absorbed power density. At the ICNIRP basic restriction $\langle \text{APD} \rangle_{1/4\text{cm}^2} \leq 10$ W/m², this implies $\text{psSAR}_{10\text{g}} \leq 0.66$ W/kg, a factor of three below the head and trunk basic restriction of 2 W/kg and a factor of six below the limb restriction of 4 W/kg.

The bound follows from energy conservation on the cube footprint, with the $\sqrt{2}$ factor covering the worst-case tilt between cube axes and body normal. The derivation and its tightness under the IEC mass rule are given below. The same surface integral that gives $\langle \text{APD} \rangle_{1/4\text{cm}^2}$ therefore controls $\text{psSAR}_{10\text{g}}$.

5.4.2.1 Derivation

Per unit body-surface area, the time-averaged flux entering tissue is APD by definition. The cube intercepts this flux over its body-surface footprint A_{fp} .

Define the dimensionless footprint ratio $g = A_{\text{fp}}/L^2$, where A_{fp} is the area of the body's planar surface intersection with the cube and L is the cube side. Total absorbed power inside the cube cannot exceed total flux entering through A_{fp} , by energy conservation:

$$P_{\text{abs,cube}} \leq \text{APD} \cdot A_{\text{fp}}. \quad (5.20)$$

Dividing by cube mass $m = \rho_m L^3$ and substituting $A_{\text{fp}} = gL^2$ returns (5.19). Equality in (5.20) requires every joule entering the footprint to deposit inside the cube, which holds in the strong-attenuation limit $\alpha L \rightarrow \infty$.

5.4.2.2 Body-cube intersection geometry

The footprint $A_{\text{fp}} = gL^2$ depends on the cube orientation relative to the body normal. For an axis-aligned cube whose z-axis aligns with $\hat{n}$, the body plane cuts

perpendicular to a cube face and the intersection is the constant $L \times L$ square: $g = 1$. The geometric maximum cross-section of an axis-aligned cube by an arbitrary plane is achieved by a face-diagonal cut (plane normal $(1, 1, 0)/\sqrt{2}$) and equals $\sqrt{2} L^2$, giving $g = \sqrt{2}$. The body-diagonal hexagonal cut (plane normal $(1, 1, 1)/\sqrt{3}$) is smaller at $3\sqrt{3}/4 \approx 1.30$, so the face-diagonal rectangle sets the universal ceiling.

The IEC/IEEE 62704-1 mass constraint tightens this. The $\sqrt{2} L^2$ cross-section occurs at the cube center, where each half holds 50% of the cube volume. That placement violates the 90%-tissue rule. Pushing the cube deeper into tissue to recover the 90% rule moves the body cut from the cube center toward an edge, where the cube cross-section is smaller. The realistic worst-case g under the IEC mass rule sits between 1 and $\sqrt{2}$, depending on the tilt between cube axes and $\hat{n}$.

5.4.2.3 Tightness

For a homogeneous absorbing half-space with field amplitude decay rate α , the SAR depth profile is $\text{SAR}(z) = \text{SAR}(0) e^{-2\alpha|z|}$ and energy conservation pegs the surface SAR to the absorbed flux, $\rho_m \text{SAR}(0) = 2\alpha \text{APD}$. The face-flush cube average evaluates to

$$\langle \text{SAR} \rangle_{\text{cube}} = \frac{\text{APD}}{\rho_m L} (1 - e^{-2\alpha L}), \quad (5.21)$$

so the bound (5.19) at $g = 1$ is loose by the capture-fraction factor $C(\alpha L) = 1 - e^{-2\alpha L}$.

Here, C is the fraction of the entering power absorbed within the cube depth L in this homogeneous face-flush example. The parameter α is the field-amplitude attenuation rate. For the 10 g homogeneous example, $m = 10$ g, $\rho_m = 1000$ kg/m³, and $L = (m/\rho_m)^{1/3} \approx 21.5$ mm, where m denotes cube mass. Table 5.7 lists C on skin across frequency. Above 5 GHz the bound is exact to within a few percent. Below 1 GHz the bound is loose by approximately 50% on skin and more on fat where the field penetration depth exceeds the cube side.

Table 5.7: Capture fraction $C(\alpha L) = 1 - e^{-2\alpha L}$ on skin, where α is the field amplitude decay rate and $L = 21.5$ mm.

f [GHz]	$1/(2\alpha)$ [mm]	$2\alpha L$	C
0.9	19.9	1.1	0.67
2.45	11.3	1.9	0.85
5	5.3	4.1	0.98
10	1.9	11.3	1.00
28	0.46	46.7	1.00
60	0.24	89.9	1.00

A Monte Carlo cube search over 15 surface points on the Thelonious mesh, four polarization configurations, and five incidence directions per point across 1–28 GHz returns a median bound-to-numerical ratio of 1.30 and a maximum of

1.46, consistent with the combined effect of the capture fraction and the geometric prefactor g .

5.5 Incoherent-model implications and regime of validity

5.5.1 Computational structure

The matrix form (5.10) is a single-hidden-layer rectified-linear ‘network’ whose weights are the path directions and powers from a ray tracer [25]. Three properties follow.

First, the network is differentiable in every input. The smooth GELU activation (5.16) replaces the hard $[\cdot]_+$ gate, preserving the chain rule. Gradients of regulatory quantities propagate to antenna positions, antenna orientations, beam codebooks, and reconfigurable-intelligent-surface phases through standard back-propagation. End-to-end exposure assessment in current practice requires a per-scenario FDTD evaluation on the user phantom as the back-end step [36, 37]. With the closed form replacing that step, exposure-constrained network design becomes a continuous optimization problem, because of a speed increase and the availability of gradients on each differentiable computation.

Second, the per-triangle absorbed-power map for $M_\Sigma \approx 10^4$ triangles¹ and $N \approx 10^2$ paths is one matrix-vector multiply on a modern GPU, evaluated in under 10 ms. The cost is independent of frequency. Against an FDTD reference whose cost scales as f^4 , the speed advantage grows by roughly 10^4 from 6 to 60 GHz, exactly the band where the Fresnel approximation is sharpest and the closed form holds pointwise within 3% of FDTD (Table 5.8). The cosine gate is rectified shading. The visibility matrix $\mathbf{V}$ is ambient occlusion, one of the most optimized computations in real-time rendering [14].

Third, the whole-body identity (5.13) factorizes the body dependence into a single scalar $A_{\text{ab}} = \bar{\eta} A$. For a given phantom and posture, $\bar{\eta}$ is computed once, in tens of milliseconds, and cached. Population studies that previously required one FDTD solve per body and per direction reduce to one Fresnel quadrature shared across the population and one occlusion pass per body.

We highlight three potential applications. First, dosimetry can be computed in real time, because each evaluation takes about 10 ms, well below the timescale on which the body pose and environment change, given an accurate digital twin of both. Second, exposure metrics can be optimized under design constraints, because the method is differentiable end to end. Third, large-scale dosimetric assessment across diverse populations is possible and useful at the city scale, e.g., for epidemiological studies such as the GOLIAT project [38].

¹Note that the number of triangles is arbitrary. As long as the geometric shadow is kept constant, SAR_{wb} results will not change. A correct validation with FDTD requires similar geometric accuracy of the underlying mesh.

5.5.2 Regulatory implications

Within the constant-transmission geometric model, whole-body ICNIRP compliance reduces to one inequality on three precomputed scalars (Eq. (5.17)). The ICNIRP general-public reference level above 6 GHz is 10 W/m² [1]. Reference levels are incident-field limits intended to imply compliance with the underlying basic restrictions, including 0.08 W/kg whole-body SAR. Setting $\text{IPD}_{\max} = 10 \text{ W/m}^2$ in (5.17) gives $m/A \geq 33.9 \text{ kg/m}^2$ at $\bar{T} = 0.543$ (28 GHz on skin). The infant, child and adolescent thresholds in Table 5.6 are 6.2, 7.6 and 9.9 W/m², respectively. The reference level exceeds these sufficient model thresholds by 61%, 32% and 1%. Their values follow from the geometric directional bound. A particular body and illumination can have lower absorption, so the actual cross section determines whether the basic restriction is reached.

The lower thresholds for smaller bodies in Table 5.6 connect this model to the child–adult differences in Chapter 2. For a uniform plane wave, the absorption-cross-section identity used in (2.7) is

$$\text{SAR}_{\text{wb}} = \text{IPD} \frac{\text{ACS}_{\text{wb}}}{m}.$$

At 10 W/m², the 0.08 W/kg restriction is exceeded when $\text{ACS}_{\text{wb}}/m > 0.008 \text{ m}^2/\text{kg}$. The child models have less absorbing area than the adult models and a larger absorbing area per kilogram. Chapter 2 finds whole-body SAR values of 145% and 122% of the restriction for Thelonious and Eartha in their largest simulated configurations at 2140 MHz. Thelonious averages 93% over the twelve direction–polarization cases. Infants and newborns fall outside that study and deserve separate attention. Age alone cannot determine their absorption per kilogram, because body proportions, posture and tissue properties also affect the cross section. The sufficient thresholds in Table 5.6 show this sensitivity. The actual cross section is needed to determine a crossing for a particular anatomy and exposure.

ICNIRP discusses child whole-body SAR crossings and keeps the reference levels after considering dosimetric uncertainty and thermal response [1, pp. 496, 512–513]. A larger surface area per unit mass also increases heat loss per kilogram. In a simple steady heat balance, $\text{IPD} \text{ACS}_{\text{wb}} = h_{\text{eff}} A \Delta T$, where h_{eff} is an effective heat-transfer coefficient and ΔT a uniform temperature rise. At the same incident power density and with the same ACS_{wb}/A and h_{eff} , the temperature rise is independent of A/m . This conditional balance helps explain the thermal rationale. Infant thermoregulation, clothing and ambient conditions require separate assessment, and a whole-body SAR crossing alone does not determine the resulting core-temperature rise.

5.5.3 Regime of validity

The method predicts absorption for a specific body geometry, posture, tissue model and incident field. The leading approximation treats each illuminated surface patch

Table 5.8: Frequency-band limits of (5.13) on a human-adult body. Quantitative validity covers 1–100 GHz on whole-body absorbed power, 6–100 GHz pointwise on the surface.

Band	Surface law	Whole-body identity
below 300 MHz	other physics: resonance and hot-spots	FDTD required
0.3–1 GHz	qualitative, 10%–30% Mie underestimate	qualitative, T_{lay} recovers the dip
1–6 GHz	integrated within 5%–10%, local map loses pointwise meaning	quantitative, T_{lay} replaces T_0
6–100 GHz	surface approximation, with local errors dependent on incidence and geometry	quantitative, Brewster compensation sharpest

as a planar lossy medium and represents body shadowing geometrically. The layered model includes internal reflections in a chosen planar stack, and the diffraction model adds selected high-frequency corrections. The model omits finite-body resonances, general internal scattering and antenna–body coupling. Whole-body and spatially averaged predictions can remain useful when pointwise errors are larger, but their accuracy must be checked for the frequency, body and exposure considered.

Table 5.8 summarizes the validity by frequency band. Equations (5.9) and (5.13) hold quantitatively above approximately 1 GHz on whole-body absorbed power and above approximately 6 GHz pointwise on the surface, with documented sub-6 GHz behavior from (5.14). The low-frequency boundary is set by three independent physical scales: body opacity, the body-scale Mie regime, and whole-body resonance. The high-frequency boundary is set by two, the softening of the pseudo-Brewster compensation and skin surface roughness, both gentler than the low-frequency boundary.

The surface law requires the body to be optically thick to the incident wave: the tissue skin depth must stay smaller than the body characteristic dimension, otherwise the wave passes through rather than being absorbed at the surface. This opacity criterion places the lower validity limit near 700 MHz–1 GHz for limbs and near 250 MHz for a torso. The tissue-property database [20] gives muscle skin-depth values that exceed limb cross-sections below approximately 1 GHz and torso cross-sections below approximately 250 MHz.

The Mie regime sets a second lower limit. The geometric-optics asymptote holds with sub-percent residual once $ka \gtrsim 30$ on a body characteristic dimension, and Section 5.3.2 quantifies the residual on body-scale spheres. Whole-body resonance dominates below approximately 300 MHz, where the body acts as a half-wave dipole and surface absorbed power is unrelated to internal hot-spots [39]. Below this frequency the framework reduces to volumetric solvers.

The pseudo-Brewster compensation weakens above 200–250 GHz, where the Azzam high-index criterion $|\tilde{n}| > 2.5$ weakens and worst-case angular varia-

tion grows from 5.6% at 28 GHz to approximately 10% at 250 GHz and 15% at 300 GHz, comparable to the dielectric uncertainty on T_0 (Fig. 5.9). The skin refractive-index modulus from the IT'IS database [19, 20] is 4.84 at 28 GHz, 3.68 at 60 GHz, and 3.01 at 100 GHz, and extrapolation puts $|\tilde{n}|$ near 2.5 around 200–250 GHz, approximately 2.2 at 300 GHz, and 1.8–2 at 1 THz.

Skin roughness sets an upper limit near 1 THz, where the Rayleigh criterion $h \cos \theta / \lambda < 1/8$ is violated on papillary-ridge-scale features and diffuse scattering becomes the dominant correction. Skin features stratify into stratum-corneum microtexture at 10–100 μm , papillary ridges at 0.4–0.5 mm spacing, and gross body curvature at centimeters. The wavelength is 3 mm at 100 GHz, 1 mm at 300 GHz, 0.3 mm at 1 THz. The Rayleigh criterion is met at 100 GHz on ridge-scale features and is marginal at 300 GHz.

For sources in the reactive near field ($d < \lambda/(2\pi)$), that is 1.7 mm at 28 GHz), evanescent waves and antenna-body impedance coupling require full-wave simulation. Outside this regime, the law applies pointwise with spatially varying inputs.

Measurements place the dielectric properties of biological tissue within approximately 20% at mmWave [23]. This input uncertainty produces $\pm 7\%$ on T_0 through the sublinear propagation derived in Section 5.3.7, and it dominates the error budget at every operating regime where the surface law applies.

5.6 Coherent absorption and exposure-constrained beamforming

When relative phases vary at random, the cross-terms average out and the paths add in power. The incoherent law derived above describes this limit. A downlink precoder controls these phases, so the cross-terms can remain. We include them and write exposure as a quadratic form in the precoder. The coherent formulation uses the polarization-aware Fresnel transmission of each path. The scalar simplification in Section 5.2.5 remains optional.

The operator must evaluate all applicable exposure limits. Above 6 GHz, the 2020 ICNIRP guidelines [1] set a local APD limit of 20 W/m² for the general public, averaged over 4 cm² on the body surface. Above 30 GHz, a second local limit applies over 1 cm². It supplements the 4 cm² limit and is capped at 40 W/m². The whole-body SAR restriction also applies. The first limit reached sets the transmit-power ceiling of the BS. Fast estimates let the BS evaluate these limits during design and operation.

Commercial BSs rarely reach a downlink exposure limit.² The as low as reasonably achievable (ALARA) principle still favors lower exposure.

Hochwald and Love [40, 41] introduced the SAR matrix formulation for exposure-aware beamforming. Here, the SAR averaged over a measurement volume is written as a Hermitian quadratic form $\mathbf{x}^H \mathbf{S} \mathbf{x}$ in the precoder $\mathbf{x}$ of an M -element

²Military systems and transmitters near occupational workers can reach a downlink exposure limit.

transmitter, with $\mathbf{S}$ the SAR matrix. In that setting the transmitter is the user's handset or UE. Building on [40, 41], Ying et al. [15] solve the exposure-constrained SNR problem in closed form, the optimal precoder a regularizer-shifted matched filter, and Ebadi-Shahrivar et al. [42] give a compliance test whose number of measurements grows linearly with the element count. Later work extends the form to multi-user MIMO with limited channel-state information [43]. All of this prior work addresses uplink handset self-exposure, where the user's own device radiates against a fixed head or body geometry a few centimeters away. In the BS downlink, the body stands in the far-field of the array, and the relevant channel is the ray-traced propagation channel, not a fixed device uplink scenario.

In existing work, $\mathbf{S}$ is computed by full-wave FDTD simulation on an anatomical phantom, once per antenna mounting, body posture, and array-body geometry. A mesh of ten cells per wavelength reaches order 10^8 cells at 6 GHz and 10^{12} near 100 GHz. At those frequencies the simulation becomes intractable. Castellanos et al. [44] avoid the repeated simulation with a closed-form pointwise exposure matrix at body-surface samples. Each sample is a rank-one form built from the array's free-space steering response, so it has no propagation environment. The downlink-body channel is multipath, and a single free-space direction cannot represent the phase between paths that becomes significant in the coherent regime. No closed-form, ray-traced exposure operator exists for the downlink-body problem. Such an operator must stay tractable at mmWave frequencies and physically accurate for the multipath downlink-body channel.

The coherent formulation derives this exposure operator $\mathbf{Q}$ in closed form from the same propagation paths that ray tracing already produces for the communication channel, with no full-wave step in the loop. $\mathbf{Q}$ is the downlink counterpart of the Hochwald–Ying SAR matrix $\mathbf{S}$. Integrating the absorbed power density over the body surface gives $\mathbf{Q}$, an $M \times M$ Hermitian positive-semidefinite matrix. The quadratic form $\mathbf{x}^H \mathbf{Q} \mathbf{x}$ is then the whole-body absorbed power under precoder $\mathbf{x}$ of length M , the number of array elements. One small approximation of the near-tissue field, below a tenth of a percent, reduces each surface point to a squared norm of an analytical Fresnel field channel. The incoherent limit is the surface absorption law derived and validated in Sections 5.2 and 5.3. Appendix 5.A derives the grazing-incidence and self-occlusion transition factors that refine this construction at the body's shadow boundaries. For the single-stream, one-active-operator problem, the closed-form ECBF [15] works unchanged with the analytical $\mathbf{Q}$ in place of the FDTD-computed matrix.

5.6.1 System model

Figure 5.10 sets the scene: a ray-traced indoor factory used for the numerical demonstration in Section 5.7. A mast-mounted uniform rectangular array (URA) at 28 GHz serves a device beside a body phantom among the factory scatterers. The indoor scene reuses the LOS/NLOS Factory of the Future geometry introduced in Chapter 3. The two propagation scenarios use the same scene: the direct path is open under LOS, whereas the red metallic blocker closes it under NLOS. The insets

preview the field distributions produced by MRT and ECBF.

The ray-traced path model uses the following notation. Boldface lowercase and uppercase letters denote column vectors and matrices, $(\cdot)^T$ and $(\cdot)^H$ transpose and conjugate transpose, $\mathbf{I}$ the identity, and a hat a unit vector. The array has M elements and radiates with precoder $\mathbf{x} = [x_1, \dots, x_M]^T \in \mathbb{C}^M$, normalized so that $\|\mathbf{x}\|^2 = P$ is the total transmit power. The propagation environment between the array and the body produces N paths through reflection, scattering, and diffraction. Path n , for $n = 1, \dots, N$, carries the triple $(j(n), \hat{\mathbf{k}}_n, \boldsymbol{\psi}_n)$. Here, $j : \{1, \dots, N\} \rightarrow \{1, \dots, M\}$ maps each path to its originating element, $\hat{\mathbf{k}}_n$ is its direction of arrival at the body surface, and $\boldsymbol{\psi}_n \in \mathbb{C}^3$ is its complex polarization-amplitude vector orthogonal to $\hat{\mathbf{k}}_n$. That vector encodes the path amplitude at the body, the polarization state on arrival, and every propagation interaction along its path. A ray tracer, e.g. Sionna RT [25], produces $(j(n), \hat{\mathbf{k}}_n, \boldsymbol{\psi}_n)$ as its native output.

In the downlink high-frequency scope of our method, three assumptions are warranted. First, the body surface Σ is locally flat on the scale of the wavelength, so Fresnel theory applies pointwise. Local flatness weakens on the smallest features, where the curvature radius approaches the wavelength, and the curvature refinement of Section 5.6.3 improves it. Second, the penetration depth is much smaller than any body feature. At 28 GHz the power penetration depth is $\delta \sim 0.5$ mm, against curvature radii of ~ 50 mm on the torso and ~ 8 mm on the smallest features such as ears and fingers, so all power transmitted through the surface is absorbed within a thin surface layer. Third, each path reaches the body as a single plane wave: its direction $\hat{\mathbf{k}}_n$ and polarization $\boldsymbol{\psi}_n$ are common to every surface point, and only the geometric phase $e^{-ik_0 \hat{\mathbf{k}}_n \cdot \mathbf{r}}$ varies across Σ . The plane-wave assumption holds when the last-scatter point lies far from the body compared with its extent, so that wavefront curvature and the spread of arrival directions across Σ are negligible. The array-to-body range in Section 5.7 is 6 to 22 m. Reflected paths additionally require their last interaction point to remain far from the body compared with its extent. Near-field illumination lies outside the present factorization, as discussed in Section 5.6.3.

Three matrices describe the ray-traced paths. First, the element-to-path dispatch matrix is

$$\mathbf{J} \in \{0, 1\}^{N \times M}, \quad J_{nm} = \delta_{j(n), m}. \quad (5.22)$$

Second, for an observation point $\mathbf{r} \in \mathbb{R}^3$, the phase diagonal matrix is

$$\Phi(\mathbf{r}) = \text{diag}(e^{-ik_0 \hat{\mathbf{k}}_1 \cdot \mathbf{r}}, \dots, e^{-ik_0 \hat{\mathbf{k}}_N \cdot \mathbf{r}}), \quad (5.23)$$

a unitary diagonal that applies the geometric phase of each path at $\mathbf{r}$, with free-space wavenumber $k_0 = 2\pi/\lambda$. Third, the polarization matrix stacks the per-path polarization-amplitude vectors as columns,

$$\Psi = [\boldsymbol{\psi}_1, \dots, \boldsymbol{\psi}_N] \in \mathbb{C}^{3 \times N}. \quad (5.24)$$

Ψ depends on the propagation environment and the transmit-antenna patterns. It depends on neither the precoder nor the observation point.

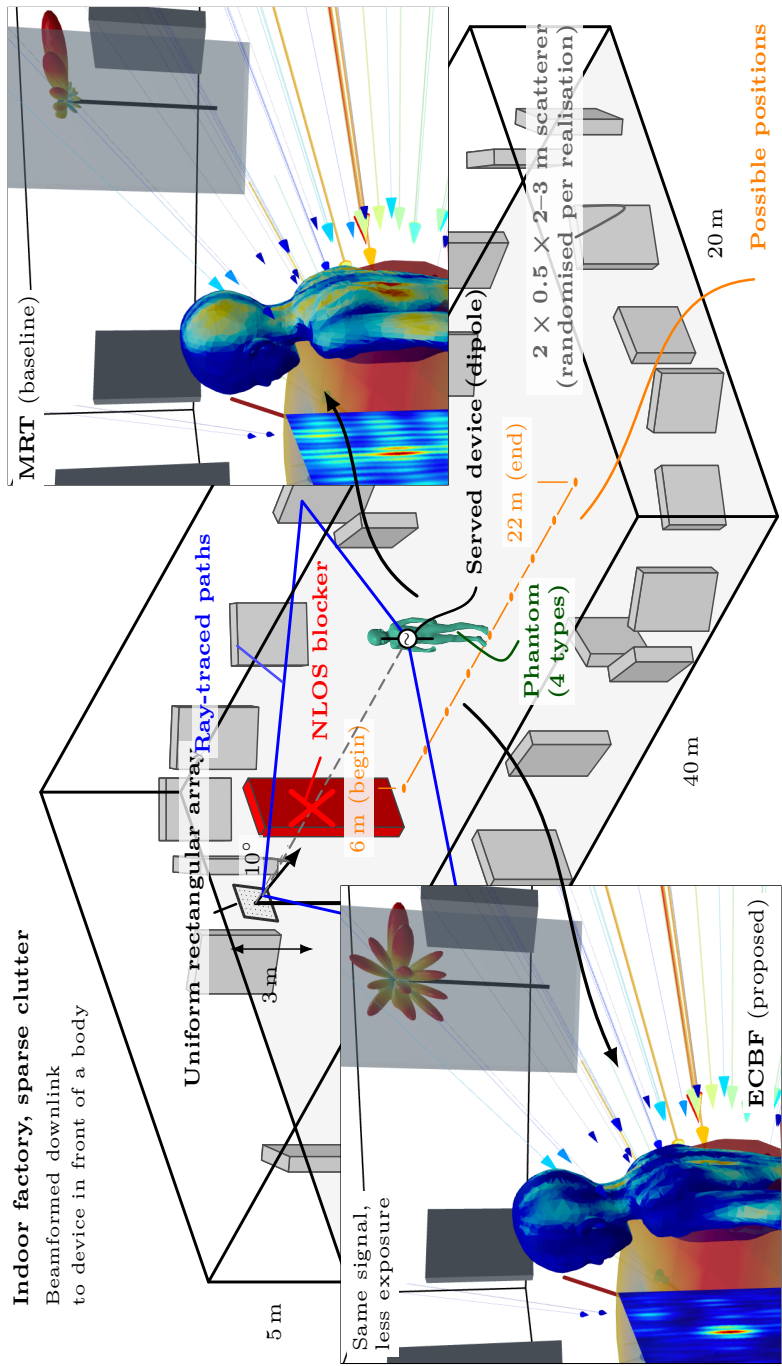


Figure 5.10: The indoor-factory configuration and beamforming effect. A mast-mounted uniform rectangular array with 10° downtilt serves nine device positions over 6–22 m. A body phantom stands behind the served dipole, and a metallic blocker blocks the direct path for the NLOS condition. The insets compare MRT and ECBF at the same received signal power: MRT concentrates the transmitted field, whereas ECBF reduces body exposure.

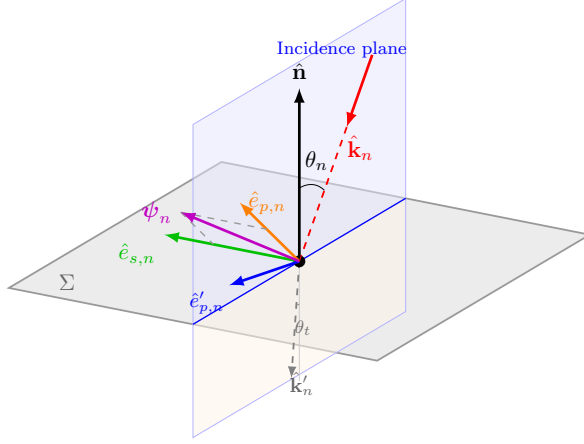


Figure 5.11: Incidence-plane geometry for path n . The polarization amplitude ψ_n is resolved on the TE basis $\hat{e}_{s,n}$ (out of plane) and the incident TM projection basis $\hat{e}_{p,n}$ (in plane). The transmitted TM vector is the exact complex vector $\mathbf{e}'_{p,n} = (\xi_n \hat{t}_n + \sin \theta_n \hat{n}) / \tilde{n}$, where $\hat{t}_n$ is the in-plane tangent and ξ_n uses the passive branch. It is not unit-normalized.

The free-space electric field at any point $\mathbf{r}$ under precoder $\mathbf{x}$ is the sum of the per-path contributions,

$$\mathbf{E}(\mathbf{r}) = \sum_n \psi_n x_{j(n)} e^{-ik_0 \hat{\mathbf{k}}_n \cdot \mathbf{r}} = \mathbf{G}(\mathbf{r}) \mathbf{x}, \quad (5.25)$$

with field channel $\mathbf{G}(\mathbf{r}) = \mathbf{\Psi} \mathbf{\Phi}(\mathbf{r}) \mathbf{J} \in \mathbb{C}^{3 \times M}$. In this factorization $\mathbf{\Psi}$ contains the environment, $\mathbf{\Phi}$ the position, and $\mathbf{J}$ the dispatch. Define the per-path excitation at $\mathbf{r}$,

$$\mathbf{c}(\mathbf{r}, \mathbf{x}) = \mathbf{\Phi}(\mathbf{r}) \mathbf{J} \mathbf{x} \in \mathbb{C}^N. \quad (5.26)$$

Entry n of $\mathbf{c}$ is the precoder weight of the originating element of path n times the geometric phase of that path at $\mathbf{r}$. This excitation is the state variable from which every coherent observable follows. The free-space field is $\mathbf{E}(\mathbf{r}) = \mathbf{\Psi} \mathbf{c}(\mathbf{r}, \mathbf{x})$, and the UE signal is $y(\mathbf{x}) = \mathbf{a}^T \mathbf{c}(\mathbf{r}_{\text{UE}}, \mathbf{x}) = \mathbf{h}^T \mathbf{x}$, with $\mathbf{h} \in \mathbb{C}^M$ the signal channel and per-path antenna projections $a_n = \mathbf{C}_R(\hat{\mathbf{k}}_n)^H \psi_n$ through the UE antenna response $\mathbf{C}_R(\hat{\mathbf{k}}) \in \mathbb{C}^3$ in direction $\hat{\mathbf{k}}$. The exposure channel of Section 5.6.2 extends the same structure to the body surface.

5.6.2 Coherent absorption

5.6.2.1 Per-path transmitted field

Figure 5.11 shows a ray entering the tissue of a human body Σ . Using geometric optics, we form the *exposure channel* from the same ray-traced paths as the signal channel. Each ray-traced path is a local plane wave that refracts through the surface by Fresnel theory and is absorbed in the tissue beneath. The transmitted fields are summed coherently rather than as powers, which keeps the interference between paths, and diffraction and curvature enter as refinements in Section 5.6.3. Figure 5.12 shows a flowchart with the signal and exposure branches before they meet in the constrained precoder.

At a surface point $\mathbf{r}$ with outward normal $\hat{\mathbf{n}}$, path n arrives with incidence cosine $\mu_n = \hat{\mathbf{n}} \cdot (-\hat{\mathbf{k}}_n)$. For a front-facing path ($\mu_n > 0$) the local TE and TM unit vectors are $\hat{\mathbf{e}}_{s,n} = \hat{\mathbf{k}}_n \times \hat{\mathbf{n}} / |\hat{\mathbf{k}}_n \times \hat{\mathbf{n}}|$ and $\hat{\mathbf{e}}_{p,n} = \hat{\mathbf{e}}_{s,n} \times \hat{\mathbf{k}}_n$. The Fresnel amplitude transmission coefficients are

$$t_{s,n} = \frac{2\mu_n}{\mu_n + \xi_n}, \quad t_{p,n} = \frac{2\tilde{n}\mu_n}{\tilde{n}^2\mu_n + \xi_n}, \quad (5.27)$$

with $\xi_n = \sqrt{\tilde{n}^2 - 1 + \mu_n^2}$ and $\text{Re}(\xi_n) > 0$. Writing $k_0\xi_n = \beta_n - i\alpha_n$, where $\alpha_n = -k_0 \text{Im}(\xi_n) > 0$ is the depth-attenuation constant, the depth factor inside tissue is $e^{-ik_0\xi_n z} = e^{-\alpha_n z} e^{-i\beta_n z}$. The transmitted field points along the refracted directions. The TE part keeps $\hat{\mathbf{e}}_{s,n}$, and the TM part follows the refracted direction $\hat{\mathbf{e}}'_{p,n}$, which the high tissue index tilts to within $O(1/|\tilde{n}|)$ of the surface tangent. The transmitted electric field of path n at depth z is then

$$\begin{aligned} \mathbf{E}_n^{\text{trans}}(\mathbf{r}, z) &= (t_{s,n}\psi_{s,n}\hat{\mathbf{e}}_{s,n} + t_{p,n}\psi_{p,n}\hat{\mathbf{e}}'_{p,n}) \\ &\quad \times x_{j(n)} e^{-ik_0\hat{\mathbf{k}}_n \cdot \mathbf{r}} e^{-ik_0\xi_n z} V(\mathbf{r}, \hat{\mathbf{k}}_n) H(\mu_n), \end{aligned} \quad (5.28)$$

with $\psi_{s,n} = \hat{\mathbf{e}}_{s,n} \cdot \boldsymbol{\psi}_n$ and $\psi_{p,n} = \hat{\mathbf{e}}_{p,n} \cdot \boldsymbol{\psi}_n$ the incident amplitudes, and H the Heaviside step function that sets back-facing paths to zero.

The factor $V(\mathbf{r}, \hat{\mathbf{k}}_n) \in \{0, 1\}$ is the binary self-shadowing visibility for path n at $\mathbf{r}$, one when an unobstructed ray reaches $\mathbf{r}$ from $\hat{\mathbf{k}}_n$ and zero when another body part occludes it. This is the ambient-occlusion term of the computer-graphics literature [12–14], and it removes self-shadowed contributions from the coherent sum. The amplitude, visibility factors, and transmitted directions define a per-path Fresnel transmission operator $\mathbf{F}_n(\mathbf{r})$ that maps the incident polarization $\boldsymbol{\psi}_n$ to the transmitted surface field $\mathbf{F}_n(\mathbf{r})\boldsymbol{\psi}_n$, rank two and set to zero on self-shadowed paths. The total field is the coherent sum $\mathbf{E}^{\text{trans}} = \sum_n \mathbf{E}_n^{\text{trans}}$, and the APD at $\mathbf{r}$ is the ohmic loss integrated over depth,

$$S_{\text{ab}}(\mathbf{r}) = \frac{\sigma}{2} \int_0^\infty |\mathbf{E}^{\text{trans}}(\mathbf{r}, z)|^2 dz. \quad (5.29)$$

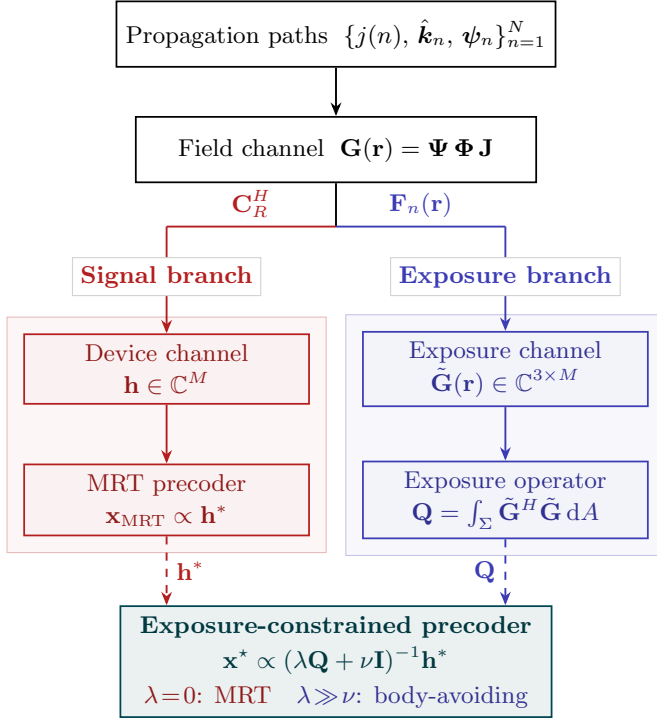


Figure 5.12: Flowchart of the shared signal and exposure channel. The branches share the path dispatch and phase, but use different amplitude blocks. The signal branch gives $\mathbf{h}$ and MRT. The exposure branch gives $\tilde{\mathbf{G}}(\mathbf{r})$ and $\mathbf{Q}$. The branches meet in the constrained precoder $\mathbf{x}^* \propto (\lambda \mathbf{Q} + \nu \mathbf{I})^{-1} \mathbf{h}^*$, with Lagrange multipliers λ (exposure) and ν (power). The precoder steers power away from the body as λ grows.

5.6.2.2 Exact quadratic form

Substituting the coherent sum into Eq. (5.29) and carrying out the depth integral separates a depth factor, which depends only on the attenuation and phase of each path pair, from a surface factor, which depends only on the transmitted fields at $z = 0$. The depth factor is

$$\begin{aligned} \Lambda_{nn'} &= \int_0^\infty e^{-(\alpha_n + \alpha_{n'})z} e^{-i(\beta_{n'} - \beta_n)z} dz \\ &= \frac{1}{\alpha_n + \alpha_{n'} + i(\beta_{n'} - \beta_n)}. \end{aligned} \quad (5.30)$$

The matrix Λ is Hermitian positive-semidefinite, with diagonal $\Lambda_{nn} = 1/(2\alpha_n)$ recovering the single-path absorbed power and off-diagonal entries holding the

coherent cross-terms. The surface factor is the Gram matrix

$$D_{nn'}(\mathbf{r}) = (\mathbf{F}_n(\mathbf{r}) \boldsymbol{\psi}_n)^H (\mathbf{F}_{n'}(\mathbf{r}) \boldsymbol{\psi}_{n'}) \quad (5.31)$$

of the transmitted surface fields, Hermitian positive-semidefinite by construction. Writing the per-path excitation $\mathbf{c}(\mathbf{r}) = \boldsymbol{\Phi}(\mathbf{r}) \mathbf{J} \mathbf{x}$ of Section 5.6.1, with entries $c_n = x_{j(n)} e^{-ik_0 \hat{\mathbf{k}}_n \cdot \mathbf{r}}$, the absorbed power density is the Hermitian quadratic form

$$S_{\text{ab}}(\mathbf{r}) = \frac{\sigma}{2} \mathbf{c}(\mathbf{r})^H (\Lambda \circ D(\mathbf{r})) \mathbf{c}(\mathbf{r}), \quad (5.32)$$

where $\circ$ is the entrywise product. The Schur product theorem states that the entrywise product of two positive-semidefinite matrices is positive-semidefinite. Hence $S_{\text{ab}}(\mathbf{r}) \geq 0$ for every precoder.

5.6.2.3 Squared-norm reduction

The reduction normalizes Λ by its diagonal,

$$\Gamma_{nn'} \equiv \frac{\Lambda_{nn'}}{\sqrt{\Lambda_{nn} \Lambda_{n'n'}}} = \frac{2\sqrt{\alpha_n \alpha_{n'}}}{\alpha_n + \alpha_{n'} + i(\beta_{n'} - \beta_n)}, \quad (5.33)$$

so that $\Gamma_{nn} = 1$ by construction. The reduction sets $\Gamma_{nn'} = e^{-i(\beta_{n'} - \beta_n)\delta}$, with $\delta = 1/(2\alpha_0)$ the normal-incidence power penetration depth of Section 5.6.1. This replaces $\Lambda_{nn'}$ by an outer product, exact on the diagonal and rank one off it: path n keeps its depth-integrated amplitude $\sqrt{\Lambda_{nn}}$, with its phase referenced at the depth δ rather than at the surface. The depth δ is the centroid of the power decay profile, which is where the integrand of Eq. (5.30) samples the dephasing of the pair, so the phase error of the reduction cancels to first order. The residual is second order and small because the tissue index is high. At 28 GHz, skin has $|\tilde{n}| \approx 4.83$, which keeps every refraction angle within 13° of normal and leaves α_n and β_n nearly angle-independent, so the depth response varies negligibly from path to path. Over $(\theta_n, \theta_{n'}) \in [0^\circ, 85^\circ]^2$ the error $|\Gamma_{nn'} - e^{-i(\beta_{n'} - \beta_n)\delta}|$ stays below 0.05% with mean 0.014%, and below 0.08% across the band.

With the depth coupling rank one, the surface field of each path is a single tissue-weighted vector. Define

$$\tilde{\boldsymbol{\psi}}_n(\mathbf{r}) \equiv \sqrt{\frac{\sigma}{4\alpha_n}} e^{-i\beta_n \delta} \mathbf{F}_n(\mathbf{r}) \boldsymbol{\psi}_n \in \mathbb{C}^3, \quad (5.34)$$

stacked as $\tilde{\boldsymbol{\Psi}}(\mathbf{r}) = [\tilde{\boldsymbol{\psi}}_1(\mathbf{r}), \dots, \tilde{\boldsymbol{\psi}}_N(\mathbf{r})] \in \mathbb{C}^{3 \times N}$. The body-surface field channel then factors as

$$\tilde{\mathbf{G}}(\mathbf{r}) = \tilde{\boldsymbol{\Psi}}(\mathbf{r}) \boldsymbol{\Phi}(\mathbf{r}) \mathbf{J} \in \mathbb{C}^{3 \times M}, \quad (5.35)$$

in exact parallel with the free-space field channel $\mathbf{G}(\mathbf{r}) = \boldsymbol{\Psi} \boldsymbol{\Phi} \mathbf{J}$ of Section 5.6.1. Signal, field, and exposure channels share the dispatch matrix $\mathbf{J}$ and the phase matrix $\boldsymbol{\Phi}$ (Fig. 5.12), differing only in the per-path amplitude block: $\boldsymbol{\Psi}$ for the

free-space field, $\mathbf{a}^T$ for the UE signal, and $\tilde{\Psi}$ for the body-surface exposure. The signal branch samples one point through the UE antenna, and the exposure branch samples the whole body surface through the per-path Fresnel operator.

The APD is then the squared norm

$$S_{\text{ab}}(\mathbf{r}) = \|\tilde{\mathbf{G}}(\mathbf{r}) \mathbf{x}\|^2 = \mathbf{x}^H \tilde{\mathbf{G}}(\mathbf{r})^H \tilde{\mathbf{G}}(\mathbf{r}) \mathbf{x}, \quad (5.36)$$

with rank at most three at each surface point. The squared norm follows from the exact form Eq. (5.32). The reduction of Section 5.6.2.3 makes $\Lambda_{nn'} = \sqrt{\Lambda_{nn}} e^{i\beta_n \delta} \sqrt{\Lambda_{n'n'}} e^{-i\beta_{n'} \delta}$ an outer product, so the Schur product $\Lambda \circ D(\mathbf{r})$ becomes the Gram matrix of the tissue-weighted vectors of Eq. (5.34). The quadratic form of a Gram matrix is a squared norm, and the inner sum is $\tilde{\mathbf{G}}(\mathbf{r}) \mathbf{x}$.

5.6.2.4 Limiting cases

The coherent law recovers the surface models derived earlier in two limits. Both depend only on the exact diagonal, so they hold with or without the reduction. For a single path, Eq. (5.36) reduces to the polarization-aware Fresnel surface law at a visible surface point, and under the additional pseudo-Brewster approximation to the geometric law $S_{\text{ab}}(\mathbf{r}) = \text{APD}(\mathbf{r}) = \text{IPD } T_0 V(\mathbf{r}, \hat{\mathbf{k}}) [\mu]_+$, with T_0 the normal-incidence power transmission coefficient. When the N paths carry mutually random relative phases, the cross-terms average to zero and the expected APD is

$$\begin{aligned} \langle S_{\text{ab}}(\mathbf{r}) \rangle = (2Z_0)^{-1} \sum_n |x_{j(n)}|^2 (T_{s,n} |\psi_{s,n}|^2 + T_{p,n} |\psi_{p,n}|^2) \\ \times V(\mathbf{r}, \hat{\mathbf{k}}_n) [\mu_n]_+, \quad (5.37) \end{aligned}$$

where $T_{s,n}$ and $T_{p,n}$ are the power transmission coefficients of the two polarizations at the incidence angle of path n . This is the multi-source surface dosimetry law derived in Section 5.2.5.6. Because the self-terms are exact, this limiting law has no approximation error. Full-wave validation of the incoherent law therefore validates only the incoherent limit, not the full coherent operator. A lossy-sphere calculation in Section 5.7 provides a separate consistency test for the coherent reduction.

5.6.3 Absorption kernel

Integrating Eq. (5.36) over the body surface gives the whole-body absorbed power as a quadratic form in the precoder. The exposure operator is

$$\mathbf{Q} = \int_{\Sigma} \tilde{\mathbf{G}}(\mathbf{r})^H \tilde{\mathbf{G}}(\mathbf{r}) dA \in \mathbb{C}^{M \times M}, \quad (5.38)$$

so that $P_{\text{abs}} = \mathbf{x}^H \mathbf{Q} \mathbf{x}$ is the whole-body absorbed power under precoder $\mathbf{x}$. By construction, $\mathbf{Q}$ is Hermitian positive-semidefinite, with rank at most $\min(M, 3M_{\Sigma})$, where M_{Σ} counts the integration triangles on the body mesh. The

trace $\text{tr}(\mathbf{Q})$ equals the expected absorbed power under isotropic random precoding, scaled by the transmit power per element.

$\mathbf{Q}$ is the downlink counterpart of the Hochwald-Ying SAR matrix $\mathbf{S}$ [15, 41], integrated over the body surface rather than a fixed tissue volume, so it returns whole-body absorbed power directly. An even coarser reduction keeps only the diagonal of $\mathbf{Q}$ and discards every off-diagonal entry. The discarded off-diagonal entries are the coherent coupling between paths, and Section 5.7 shows most of the operator energy is in them.

The precoder enters the surface integral only through the element weights $x_{j(n)}$, which multiply the incident polarization of each path. Writing $\mathbf{e}_n = x_{j(n)} \boldsymbol{\psi}_n$ and using $\tilde{\mathbf{G}}(\mathbf{r}) = \tilde{\Psi}(\mathbf{r})\Phi(\mathbf{r})\mathbf{J}$ from Eq. (5.35), the whole-body absorbed power splits into a phantom part and a scene part,

$$P_{\text{abs}} = \sum_{n,n'} \mathbf{e}_n^H \mathbf{T}(\hat{\mathbf{k}}_n, \hat{\mathbf{k}}_{n'}) \mathbf{e}_{n'}, \quad (5.39)$$

where the absorption kernel is the 3×3 matrix

$$\begin{aligned} \mathbf{T}(\hat{\mathbf{k}}, \hat{\mathbf{k}}') &= \frac{\sigma}{4\sqrt{\alpha(\hat{\mathbf{k}})\alpha(\hat{\mathbf{k}}')}} \\ &\times \int_{\Sigma} \mathbf{F}(\mathbf{r}; \hat{\mathbf{k}})^H \mathbf{F}(\mathbf{r}; \hat{\mathbf{k}}') e^{-ik_0(\hat{\mathbf{k}}' - \hat{\mathbf{k}}) \cdot \mathbf{r}} dA. \end{aligned} \quad (5.40)$$

Here $\mathbf{F}(\mathbf{r}; \hat{\mathbf{k}})$ is the per-path Fresnel operator of Section 5.6.2 for a wave arriving along $\hat{\mathbf{k}}$, and $\alpha(\hat{\mathbf{k}})$ its depth attenuation. The kernel depends on the phantom alone. It is independent of the path count and the scene, one fixed object per phantom and frequency, evaluated once and reused for every array and every scene. The diagonal $\mathbf{T}(\hat{\mathbf{k}}, \hat{\mathbf{k}})$ is the body's directional absorptivity along $\hat{\mathbf{k}}$. The off-diagonal $\mathbf{T}(\hat{\mathbf{k}}, \hat{\mathbf{k}}')$ is the body's spatial Fourier component at the difference wave vector $\mathbf{q} = k_0(\hat{\mathbf{k}}' - \hat{\mathbf{k}})$, the coherent coupling that a diagonal reduction discards. Per-phantom kernels are pre-computed once per frequency and made available publicly for each phantom.

A scene samples the kernel at its ray directions. Contracting the kernel with the incident polarizations of one path pair gives the path-pair Gram matrix

$$M_{nn'} = \boldsymbol{\psi}_n^H \mathbf{T}(\hat{\mathbf{k}}_n, \hat{\mathbf{k}}_{n'}) \boldsymbol{\psi}_{n'}, \quad (5.41)$$

an $N \times N$ Hermitian positive-semidefinite matrix whose diagonal is the single-path absorbed power and whose off-diagonal is the coherent coupling. Grouping the paths by the element that radiates each, through the dispatch $\mathbf{J} \in \{0, 1\}^{N \times M}$ of Section 5.6.1, the operator of Eq. (5.38) factors as

$$\mathbf{Q} = \mathbf{J}^T \mathbf{M} \mathbf{J}. \quad (5.42)$$

The factorization separates the array from the body. The dispatch $\mathbf{J}$ is combinatorial, a $\{0, 1\}$ assignment of each path to the element that radiates it. The path-pair Gram matrix $\mathbf{M}$ is the continuous part, the scene's sampling of the fixed body through its

path geometry, shape, and tissue, and holds none of the array hardware. A change of array updates only $\mathbf{J}$, whereas a change of scene updates only $\mathbf{M}$. The body enters both only through the pre-computed kernel $\mathbf{T}$ of Eq. (5.40).

For a surface-only refinement, choose a different per-path Fresnel operator $\mathbf{F}(\mathbf{r})$ in Eq. (5.40). Any bounded linear $\mathbf{F}(\mathbf{r}) : \mathbb{C}^3 \rightarrow \mathbb{C}^3$ from the incident polarization to the transmitted surface field keeps $\mathbf{Q} = \int_{\Sigma} \tilde{\mathbf{G}}^H \tilde{\mathbf{G}} dA$ an integral of Gram matrices, so the operator stays positive-semidefinite and the beamformer of Section 5.6.4 applies without change. The factorization $\mathbf{Q} = \mathbf{J}^T \mathbf{M} \mathbf{J}$ and its assembly are unchanged.

Surface-only refinements include shadow-edge diffraction through a Fock transition gate on the Fresnel coefficients, cross-body diffraction, surface curvature, broadband operation, and the tissue model of a chosen phantom. A Fock transition factor is a high-frequency correction near the boundary between illuminated and shadowed surface. Appendix 5.A gives its construction and the underlying diffraction theory [45]. In the uplink at mmWave frequencies, the body remains mostly in the radiative far field of the UE, but the spherical wavefronts require the use of spherical Green functions instead of plane waves. A multilayer stack is different: it replaces the homogeneous scalar depth factor with a vector depth Gram. Exact layered TM forward and backward fields have opposite normal components, so a rank-one reduction must be validated for the chosen stack. These refinements change the surface operator but preserve its Gram-matrix form.

Above 6 GHz, the local APD restriction applies alongside the whole-body restriction, so its evaluation requires the APD averaged over a small patch. Let $\omega_A(\mathbf{r}; \mathbf{r}_0)$ be the normalized averaging mask of the 4 cm^2 patch centered at $\mathbf{r}_0$, the spatial-averaging area of the ICNIRP FR2 basic restriction: $\omega_A = 1/A$ inside the patch and zero outside, so that $\int_{\Sigma} \omega_A dA = 1$. The local exposure operator is

$$\mathbf{Q}_A(\mathbf{r}_0) = \int_{\Sigma} \omega_A(\mathbf{r}; \mathbf{r}_0) \tilde{\mathbf{G}}(\mathbf{r})^H \tilde{\mathbf{G}}(\mathbf{r}) dA = \mathbf{J}^T \mathbf{M}_{A, \mathbf{r}_0} \mathbf{J}, \quad (5.43)$$

with $\mathbf{M}_{A, \mathbf{r}_0}$ the masked path-pair Gram matrix obtained by applying the same mask to the path-pair surface integral. The spatially averaged APD is $\langle \text{APD} \rangle_A(\mathbf{r}_0) = \mathbf{x}^H \mathbf{Q}_A(\mathbf{r}_0) \mathbf{x}$, in W/m^2 . With the unnormalized mask $\omega \equiv 1$, the integral returns the whole-body operator $\mathbf{Q}$. The mask multiplies only the surface integrand, so the local operator has the same factorization. Section 5.6.4 constrains this operator with the local basic restriction.

5.6.4 Exposure-Constrained Beamforming (ECBF)

The 2020 ICNIRP guidelines [1] set a whole-body restriction and one or more applicable local peak-absorption restrictions. A compliant BS must satisfy all of them on every exposed body at all times. A BS serves K users with precoders $\{\mathbf{x}_k\}_{k=1}^K$. One ray-traced environment gives a single path set shared across all bodies in the scene, so the dispatch $\mathbf{J}$ and the phase Φ are common, and each body u has its own Fresnel filter through the per-body operators $\mathbf{Q}^{(u)} = \mathbf{J}^T \mathbf{M}^{(u)} \mathbf{J}$ and

$\mathbf{Q}_A^{(u)}(\mathbf{r}_0) = \mathbf{J}^T \mathbf{M}_{A,\mathbf{r}_0}^{(u)} \mathbf{J}$ of Section 5.6.3. The ECBF sum-rate problem is

$$\begin{aligned} & \max_{\{\mathbf{x}_k\}} R(\{\mathbf{x}_k\}) \\ & \text{s.t. } \sum_k \mathbf{x}_k^H \mathbf{Q}^{(u)} \mathbf{x}_k \leq m_u \text{SAR}_{\text{wb},\text{lim}}, \quad \forall u, \\ & \quad \max_{\mathbf{r}_0} \sum_k \mathbf{x}_k^H \mathbf{Q}_A^{(u)}(\mathbf{r}_0) \mathbf{x}_k \leq S_{\text{ab},\text{lim}}, \quad \forall u, \\ & \quad \sum_k \|\mathbf{x}_k\|^2 \leq P, \end{aligned} \quad (5.44)$$

with m_u the mass of body u , $\text{SAR}_{\text{wb},\text{lim}}$ and $S_{\text{ab},\text{lim}}$ the whole-body and local basic restrictions, and P the transmit-power limit. The first constraint limits the whole-body averaged specific absorption rate (wbSAR) of body u , and the second limits its peak spatially averaged APD for the area represented by $\mathbf{Q}_A$. The second row is written for one local averaging area. Where a second area applies, the same row is repeated with its corresponding operator and limit. Every operator is positive-semidefinite, so each exposure constraint is convex in the precoders.

The general-public local APD limit averaged over 4 cm^2 is 20 W/m^2 . Above 30 GHz , the 1 cm^2 average has a limit of 40 W/m^2 and is an additional restriction. A compliant precoder enforces every applicable local restriction over the complete body surface. It adds any violated patch constraint until the complete surface satisfies each limit.

When only one local specification applies, one body of mass m and surface area $|\Sigma|$ has one whole-body and one local restriction, which reduce to one ratio. Both scale linearly with the transmit power $\|\mathbf{x}\|^2$ at fixed precoder shape. The whole-body restriction is reached at the transmit power $P_{\text{tx}}^{\text{wb}} = \|\mathbf{x}\|^2 \text{SAR}_{\text{wb},\text{lim}} m / \mathbf{x}^H \mathbf{Q} \mathbf{x}$, and the local restriction at $P_{\text{tx}}^{\text{loc}} = \|\mathbf{x}\|^2 S_{\text{ab},\text{lim}} / \max_{\mathbf{r}_0} \mathbf{x}^H \mathbf{Q}_A(\mathbf{r}_0) \mathbf{x}$. Their ratio is the *binding ratio* $R_{\text{bind}}^{\text{wb}>\text{loc}}$,

$$R_{\text{bind}}^{\text{wb}>\text{loc}} = \frac{P_{\text{tx}}^{\text{wb}}}{P_{\text{tx}}^{\text{loc}}} = \frac{\eta_A(\mathbf{x})}{\eta_{\text{crit}}}, \quad \eta_A(\mathbf{x}) = |\Sigma| \frac{\max_{\mathbf{r}_0} \mathbf{x}^H \mathbf{Q}_A \mathbf{x}}{\mathbf{x}^H \mathbf{Q} \mathbf{x}}, \quad (5.45)$$

where the norm factors cancel and the second equality follows by substitution, with $\eta_A(\mathbf{x})$ the precoder's peak-to-mean contrast on the body and $\eta_{\text{crit}} = (S_{\text{ab},\text{lim}}/\text{SAR}_{\text{wb},\text{lim}}) |\Sigma|/m$ the body threshold. $R_{\text{bind}}^{\text{wb}>\text{loc}} > 1$ means the local restriction is reached before the whole-body restriction as transmit power increases. The ratio $S_{\text{ab},\text{lim}}/\text{SAR}_{\text{wb},\text{lim}}$ is 250 kg/m^2 for both the occupational ($100/0.4$) and the general-public ($20/0.08$) limits, so $\eta_{\text{crit}} = 250 |\Sigma|/m$. Above 30 GHz no single binding ratio describes compliance. The first-binding state is instead the smallest permitted transmit-power scale among wbSAR and the two local averages. Since $|\Sigma|/m$ scales as $m^{-1/3}$, a smaller body has a larger threshold. Section 5.7 measures the predicted crossover.

The general problem has no closed form because its constraints must hold for every exposed body u and every applicable patch center $\mathbf{r}_0$. With one body, one active exposure constraint, and one data stream, the design maximizes received signal power subject to that constraint and the power limit,

$$\max_{\mathbf{x}} |\mathbf{h}^T \mathbf{x}|^2 \quad \text{s.t. } \mathbf{x}^H \mathbf{Q} \mathbf{x} \leq m \text{SAR}_{\text{wb},\text{lim}}, \quad \|\mathbf{x}\|^2 \leq P, \quad (5.46)$$

written here for the whole-body restriction. The local case replaces $\mathbf{Q}$ by $\mathbf{Q}_A(\mathbf{r}_0)$ and the limit by $S_{\text{ab},\text{lim}}$. The objective is the squared modulus of a linear functional of $\mathbf{x}$, and both constraints are convex quadratic forms, so this is a non-convex quadratically constrained quadratic program (QCQP) with two positive-semidefinite constraints. Strong duality holds for this class [15], so the stationarity condition below characterizes the global optimum rather than a local one.

Let $\mathbf{B} = \lambda \mathbf{Q} + \nu \mathbf{I}$. When $\mathbf{B}$ is nonsingular, stationarity gives the maximizer of Eq. (5.46) in closed form,

$$\mathbf{x}^* = c^* \frac{\mathbf{B}^{-1} \mathbf{h}^*}{\|\mathbf{B}^{-1} \mathbf{h}^*\|}, \quad (5.47)$$

with $0 < c^* \leq \sqrt{P}$ the largest feasible amplitude and Lagrange multipliers $\lambda \geq 0$ and $\nu \geq 0$ fixed by complementary slackness. At least one constraint is active: $c^* = \sqrt{P}$ when the power constraint binds, while $c^* < \sqrt{P}$ can occur when the exposure limit binds first. This is the regularizer-shifted matched filter of Ying et al. [15], derived there for the FDTD-computed SAR matrix and now using the analytical operator $\mathbf{Q}$ of Eq. (5.38) in place of the simulated one. Up to a physically irrelevant common phase, the solution is unique when $\mathbf{B}$ is nonsingular. If $\mathbf{B}$ is singular, its ordinary inverse does not exist. Replacing $\mathbf{B}^{-1}$ by its Moore–Penrose inverse $\mathbf{B}^+$ selects the minimum-norm solution; other optima can differ by a null-space component that changes neither the absorbed power nor the served signal. The form needs only $\mathbf{Q} \succeq 0$, which holds for the exact operator and every refinement of it. The only computation is one $M \times M$ element-space solve in Eq. (5.47). As an array processor, this precoder is a diagonally loaded minimum-variance distortionless response (MVDR) filter in which the body’s absorption covariance replaces the interference covariance.

The two limits of the exposure constraint are known precoders (Fig. 5.12). A slack constraint ($\lambda \rightarrow 0$) gives $\mathbf{x}^* \propto \mathbf{h}^*$, MRT. A binding constraint ($\lambda \rightarrow \infty$ at finite ν) gives $\mathbf{x}^* \approx \mathbf{Q}^{-1} \mathbf{h}^*$ when $\mathbf{Q}$ is full rank, and the projection of $\mathbf{h}^*$ onto the null space of $\mathbf{Q}$ otherwise, steering the precoder into the absorption null space of the body. Without the power limit, maximizing signal per absorbed power gives the Pareto-optimal precoder $\mathbf{x}^* \propto \mathbf{Q}^{-1} \mathbf{h}^*$. The constrained design reduces absorption without a proportional loss of signal because the signal and the body combine the same paths differently, one branch per channel in Fig. 5.12. First, the signal branch under MRT superposes scalar projections $h_j^* h_j \in \mathbb{R}_+$ at one point, whereas the body field superposes vector contributions in $\mathbb{C}^3$, so matched path magnitudes can cancel at $\mathbf{r}$ when their transmitted polarizations differ. Second, the signal channel projects each path through a scalar antenna inner product, whereas the exposure channel applies a 3×3 rank-two Fresnel operator tied to the surface normal. A grazing path still serves the signal but contributes little to absorption, because both Fresnel coefficients vanish at $\mu = 0$. Third, the signal is evaluated at the single UE point, where MRT aligns the path phases. Exposure is evaluated at every $\mathbf{r} \in \Sigma$, where each path has the extra phase $e^{-ik_0 \mathbf{k}_n \cdot (\mathbf{r} - \mathbf{r}_{\text{UE}})}$ relative to the UE, so alignment at the UE need not hold on the body.

5.7 Numerical demonstration

The numerical results use the ray-traced indoor factory shown in Fig. 5.10. The full Cartesian product spans four phantoms, three URA sizes, LOS and NLOS, 16 scene realizations (each with differently placed concrete scatterers), eight frequencies from 8 to 100 GHz, and nine served-user positions from 6 to 22 m. The first block evaluates the MRT precoder at 21 body-relative device placements and supplies the absorbed-power and binding-restriction results. The second block evaluates six whole-body ECFB limits for the chest focus point at skin contact and supplies the signal–exposure trade-off results. The focus point is the location of the dipole antenna of the UE. Incoherent dosimetry sums powers and therefore cannot determine which basic restriction binds first as transmit power increases, where peak absorption occurs, or how strongly a coherent precoder can concentrate absorption. As previewed in the insets of Fig. 5.10, the exposure-constrained precoder of Section 5.6.4 then demonstrates its control over coherent concentration.

5.7.1 Configuration

Figure 5.10 shows the $40 \times 20 \times 5$ m factory scene, which follows the exposure scenarios of Shikhantsov et al. and Wydaeghe et al. [36, 46]. Its Poisson-distributed metallic clutter is inspired by the indoor factory with sparse clutter and a high base station (InF-SH) model of 3GPP Technical Report 38.901 [47]. A URA of isotropic, vertically polarized elements hangs at one end of the hall at 3 m height, with a 10° mechanical downtilt towards the floor. The exposed body stands in the corridor in front of the array. Sionna RT [25] ray-traces each scene once at the array phase center, using 10^6 ray samples and up to five reflection bounces. The departure direction then gives the analytical phase at every physical element of the square, half-wavelength URA [48]. This construction preserves the intended 10° panel tilt for all three array sizes. Two propagation conditions were ray-traced: LOS and NLOS, with the latter created by a $0.5 \times 2 \times 5$ m³ metallic blocker on the direct path.

Table 5.9 lists the phantoms and all the different sweep variables. It gives the average along each axis of the two tabled quantities under MRT: wbSAR in mW/kg and the peak averaged APD $S_{ab,max}^{4\text{ cm}^2}$ in mW/m², both per watt of conducted power. The calculation uses 2 304 ray-traced scenes and four phantoms, giving 9 216 body–ray combinations. Analytical expansion to 16, 64, and 256 elements gives 27 648 body–scene–array cases. The full Cartesian product spans four phantoms, both propagation conditions, 16 scene realizations, eight frequencies from 8 to 100 GHz, and nine corridor positions from 6 to 22 m of BS-to-UE range. Each configuration uses its own frequency and an array with half-wavelength element spacing at that frequency. Thus the frequency sweep changes the propagation and aperture as well as the tissue response.

Table 5.9: Sweep axes and their marginal exposure means under the MRT precoder only. Frequency-by-array entries give $\text{wbSAR} / S_{\text{ab,max}}^{4 \text{ cm}^2} [S_{\text{ab,max}}^{1 \text{ cm}^2}]$ in $\text{mW/kg} / \text{mW/m}^2$ per conducted watt. Bold marks each subtable’s maximum. All 580 608 MRT body-maps enter the marginals.

(a) Phantom [†] [49]	η_{crit}	wbSAR	$S_{\text{ab,max}}^{4 \text{ cm}^2}$
Thelonious M6	11.3	0.126	21.9
Eartha F8	8.9	0.098	22.0
Ella F26	6.9	0.073	23.0
Duke M34	6.5	0.069	23.0
(b) Freq. $\times M$	16	64	256
8 GHz	0.015 / 4.0	0.053 / 13.0	0.201 / 48.1
10 GHz	0.018 / 5.6	0.050 / 14.5	0.166 / 46.4
12 GHz	0.016 / 4.9	0.051 / 13.6	0.184 / 47.5
15 GHz	0.017 / 5.0	0.051 / 13.8	0.179 / 45.5
20 GHz	0.017 / 4.4	0.053 / 12.8	0.193 / 44.5
28 GHz	0.018 / 4.5	0.055 / 13.3	0.200 / 46.9
60 GHz	0.021 / 5.1 [7.2]	0.064 / 15.2 [20.0]	0.230 / 52.5 [66.7]
100 GHz	0.024 / 5.7 [8.0]	0.071 / 16.2 [21.4]	0.248 / 56.0 [71.2]
(c) Range $\times$ condition	LOS	NLOS	
6 m	0.505 / 121.7	0.049 / 8.6	
8 m	0.272 / 68.5	0.060 / 10.8	
10 m	0.168 / 45.0	0.049 / 8.9	
12 m	0.114 / 29.7	0.038 / 7.2	
14 m	0.079 / 21.2	0.035 / 6.3	
16 m	0.059 / 16.6	0.026 / 5.3	
18 m	0.050 / 15.0	0.029 / 6.5	
20 m	0.038 / 12.6	0.019 / 4.6	
22 m	0.034 / 10.9	0.022 / 4.8	
(d) Separation $\times$ anchor	Chest	Head	Hip
0 cm	15.1	11.0	11.2
1 cm	14.2	10.4	10.3
2 cm	13.2	9.4	9.7
3 cm	12.5	8.7	9.1
5 cm	11.5	8.3	8.5
10 cm	10.9	7.9	7.8
20 cm	10.8	7.6	7.9

[†]IT’IS Virtual Population v3.x phantoms, coded by sex and age in years. $\eta_{\text{crit}} = 250|\Sigma|/m$ is the contrast threshold of Eq. (5.45).

The chest, head, and hip anchor triangles lie along the phantom's sagittal plane at heights equal to 0.62, 0.92, and 0.52 of its body height, respectively. At each anchor, the served point moves along the triangle's outward surface normal through device separations of 0, 1, 2, 3, 5, 10, and 20 cm. The MRT block evaluates all 21 placements, giving 580 608 full-body maps. The separate ECBF block evaluates six whole-body absorbed-power limits for the chest focus point at contact, giving 165 888 body-maps. This totals 746 496 body-maps. These placement and precoder sweeps require no additional ray tracing. The exposure operator depends only on the phantom, propagation condition, scene realization, frequency, array, and corridor position. Thus, the device separation and precoder enter only through the user channel $\mathbf{h}$.

The full sweep is computationally feasible because each body-direction response is built once and reused across array sizes, placements, and precoders. An FDTD simulation of this scene requires more than 10^{12} cells for one precoder, one body, and one position. Each new precoder or position requires another simulation. The exposure operator is instead assembled from the ray-traced paths. The complete 746 496-body-map calculation completed in 2.2 hours on one NVIDIA A6000 GPU, or about 10 ms per body-map. Prior full-wave dosimetry of a comparable factory hall covered the head region of one phantom, tens of directions of arrival, and ten environment realizations on a high-performance cluster [46, 48].

5.7.2 Absorbed power

The available compliance margin is quantified first. The EIRP is set to 55 dBm, representative of a ceiling-mounted local-area BS. For the 256-element array, 316 W is the equivalent isotropically radiated power; division by the ideal array gain gives 1.2 W of conducted power. Under MRT, the worst configuration reaches 4.6% of the applicable local restriction and 3.5% of the whole-body restriction. The median configuration reaches 0.3% of its first applicable restriction. Because both quantities scale linearly with transmit power, the EIRP at which each configuration reaches a restriction does not depend on the chosen reference EIRP. Across the sweep, the local restriction is reached at a median 81.1 dBm and a worst-case 68.4 dBm. The child's whole-body average reaches its restriction at a worst-case 69.6 dBm.

Along the corridor, absorbed power depends on the channel geometry. At 6 m, the LOS means are 0.505 mW/kg and 121.7 mW/m² per conducted watt, respectively. By 22 m they decrease to 0.034 mW/kg and 10.9 mW/m². The NLOS means vary much less over the same range, from 0.049 to 0.022 mW/kg and from 8.6 to 4.8 mW/m². Thus, absorbed power depends on both the propagation condition and the BS-to-UE distance.

Moving the focus point away from the surface changes the local value. At the chest, the mean 4 cm² value at the served point decreases from 15.1 mW/m² at contact to 10.8 mW/m² at 20 cm per conducted watt. The corresponding head and hip values decrease from 11.0 and 11.2 to 7.6 and 7.9 mW/m². All 21 placements reuse the same exposure operator and differ only through the user channel.

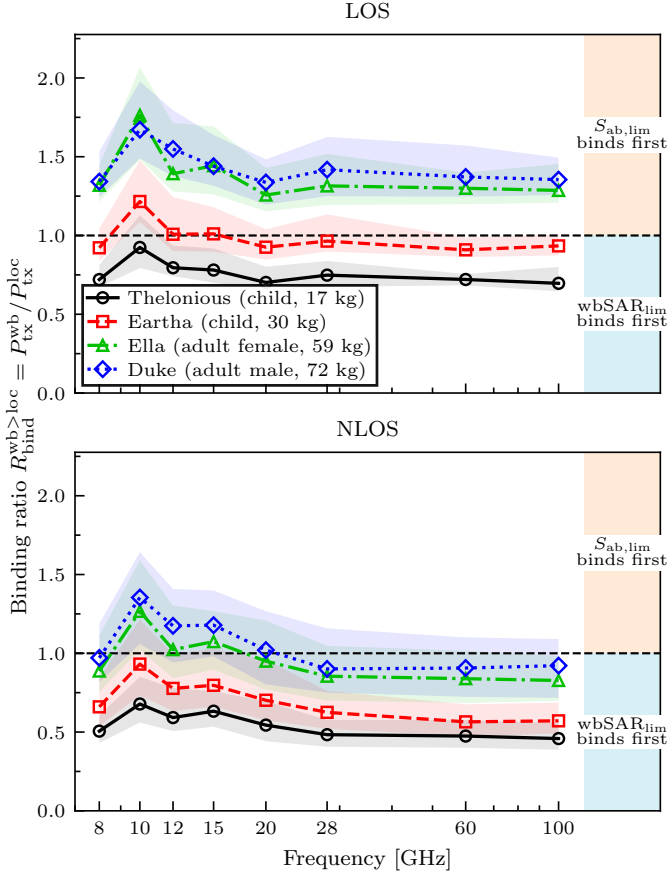


Figure 5.13: Binding ratio $R_{\text{bind}}^{\text{wb}>\text{loc}}$ against frequency for the four phantoms under LOS (top) and NLOS (bottom). The ratio compares the transmit powers allowed by wbSAR and the applicable local limit. Above the dashed line, a local restriction binds first. Above 30 GHz, the local limit is the lower of the simultaneous 1 cm^2 and 4 cm^2 limits. The lines are the medians over the remaining axes, with interquartile bands.

5.7.3 Binding restriction

Figure 5.13 shows which restriction binds first across frequency and phantom. Below 30 GHz, the binding ratio $R_{\text{bind}}^{\text{wb}>\text{loc}} = \eta_A / \eta_{\text{crit}}$ of Eq. (5.45) is the transmit power at the whole-body limit on wbSAR divided by the power at the local limit on the 4 cm^2 average $S_{\text{ab},\text{max}}^{4 \text{ cm}^2}$. $R_{\text{bind}}^{\text{wb}>\text{loc}}$ compares the transmit power allowed by each restriction: above one, the local restriction is reached before the whole-body restriction as power increases. The local restriction binds first in 99.0% of the adult LOS evaluations and 63.4% of the adult NLOS evaluations. For the two children,

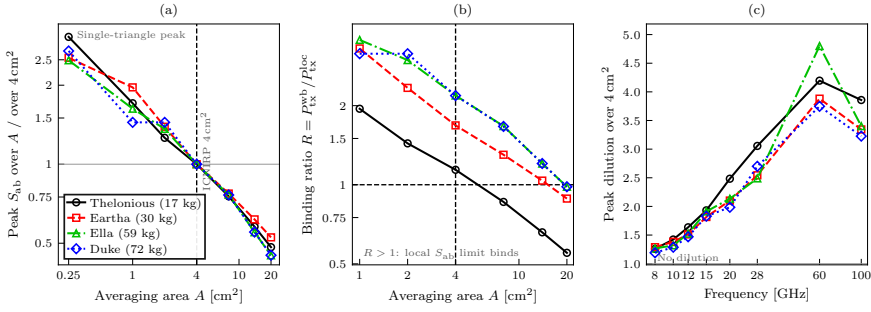


Figure 5.14: Averaging area changes the binding restriction for a fixed precoder. (a) Peak APD, normalized by its 4 cm^2 value at 28 GHz. (b) Hypothetical binding ratio R against averaging area when the local limit is held fixed. (c) Ratio of the single-triangle peak to the 4 cm^2 average under LOS, extended through 60 and 100 GHz. Above 30 GHz, complete regulatory compliance instead enforces the distinct 1 cm^2 and 4 cm^2 limits simultaneously.

the corresponding fractions are 38.2% and 13.5%. Their lower mass makes the whole-body average the lower limit in more cases. The threshold $\eta_{\text{crit}} = 250|\Sigma|/m$ ranges from 6.5 for the 72 kg adult to 11.3 for the 17 kg child (Table 5.9).

Above 30 GHz, the 1 cm^2 restriction is additional, so the local limit in Fig. 5.13 is the lower of the two local limits. Across 145 152 high-band MRT placement evaluations, wbSAR binds first in 62.08%, the 4 cm^2 average in 37.19%, and the 1 cm^2 average in 0.73%. Across the 41 472 high-band ECBF evaluations, the corresponding fractions are 57.86%, 31.78%, and 10.36%. Thus, one binding ratio is not a complete high-band compliance description. A compliant optimizer retains all three constraints.

The averaging-area sweep shows how spatial averaging changes the peak for a fixed precoder. At 28 GHz, the peak over 1 cm^2 is 1.44 to $1.96\times$ its 4 cm^2 value across the four phantoms, while the 20 cm^2 peak is 0.45 to $0.53\times$ that value (Fig. 5.14a). Thus, the hypothetical binding ratio increases as the averaging area decreases (Fig. 5.14b). At 1 and 4 cm^2 , all four phantoms are above $R = 1$. At 20 cm^2 , none are above it. The 4 cm^2 values range from 1.14 to 2.19 . This sweep holds the local limit fixed to isolate spatial averaging. In the regulatory comparison, the 1 cm^2 limit is twice the 4 cm^2 limit.

The ratio of the single-triangle peak to the 4 cm^2 average also depends on frequency (Fig. 5.14c). It is 1.19 to 1.29 at 8 GHz, 2.49 to 3.06 at 28 GHz, and reaches 3.75 to 4.80 at 60 GHz before decreasing at 100 GHz. Below 30 GHz only the 4 cm^2 restriction applies. Above 30 GHz, complete compliance evaluates the 1 cm^2 and 4 cm^2 body-maps separately with their respective limits. The binding restriction therefore depends on the propagation condition and averaging area.

Table 5.10: The impact of precoder and device separation on the median peak-to-mean contrast η of (5.48) across four Duke scene realizations at 28 GHz and 256 elements

Precoder	Focused at	LOS	NLOS	Separation-dependent
Incoherent multipath	None	3.30	2.02	No
Scrambled arrivals	None	6.60	6.46	No
MRT	UE	7.17	6.75	No
Skin-aimed ECBF	Skin point	35.56	24.82	Yes
Worst case	None	See Section 5.7.6		No

5.7.4 Coherent concentration

Figure 5.15 shows the peak-to-mean contrast for four precoders, the change in on-body peak with device separation, and the corresponding absorption-mode loading. The concentration is measured by the peak-to-mean contrast

$$\eta(\mathbf{x}) = |\Sigma| \max_{\mathbf{r} \in \Sigma} S_{\text{ab}}(\mathbf{r}) / \int_{\Sigma} S_{\text{ab}} dA, \quad (5.48)$$

the local peak per watt absorbed. This beam-dependent $\eta(\mathbf{x})$ is distinct from the geometry-only exposure fraction $\eta(\mathbf{r})$ of Section 5.2.6.1. The absorbed power scales both the numerator and denominator. Thus η is independent of array gain and transmit power. The metric measures how unevenly a given amount of absorbed power is distributed over the body.

Table 5.10 lists how four considered precoders affect the peak-to-mean contrast η . The incoherent-multipath precoder preserves the array pattern but sums the arriving paths in power, giving a contrast of 3.30 under LOS and 2.02 under NLOS. The corresponding MRT values are 7.17 and 6.75. Skin-aimed ECBF, defined as ECBF focused at a point on the skin under the strictest absorbed-power limit, reaches 35.56 and 24.82. These values are medians over four Duke scene realizations at 28 GHz and 256 elements. The worst case over all precoders is larger. Section 5.7.6 shows that it depends on the retained rank.

To separate phase coherence from array gain, the same illumination is replayed with the phase relation between arrivals randomized. The replay produces a speckle-like field. The peak-to-mean contrast is 6.60 under LOS and 6.46 under NLOS. On the same channels, MRT reaches 7.17 and 6.75. Thus, phase alignment at the user and the hot-spot on the body are unrelated. A hot-spot requires a precoder focused on the skin and sufficient aperture. Skin-aimed ECBF exceeds the scrambled result by $5.39\times$ under LOS and $3.84\times$ under NLOS.

Moving the served device away from the skin changes the two main precoders differently (Fig. 5.15b). The MRT hot-spot is generally not at the device. At contact, the median ratio between the value at the served point and the body maximum is

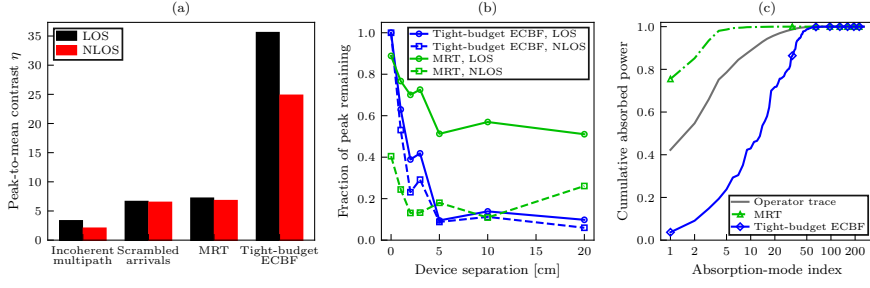


Figure 5.15: Peak-to-mean contrast η , on-body peak against device separation, and absorption-mode loading for the four precoders. (a) Median contrast under LOS and NLOS. (b) Median focus-point-to-body-peak ratio for MRT and skin-aimed ECBF as the served point moves away from the skin. Panels (a) and (b) use four Duke scene realizations at 28 GHz and 256 elements. (c) Cumulative absorbed power by absorption-mode index for one of those LOS scenes.

0.89 under LOS and 0.40 under NLOS. At 20 cm, the ratios are 0.51 and 0.26. The served-device location thus does not determine the location of peak absorption.

Skin-aimed ECBF loses its concentration with separation. At contact, almost all of its peak is at the focus point. The focus-point-to-body-peak ratio falls to 0.39 under LOS and 0.23 under NLOS at 2 cm, and reaches 0.10 and 0.06 at 20 cm. Figure 5.15b shows this decrease. Thus, this precoder concentrates absorption only when focused close to the skin. The MRT precoder does not have this concentration.

Strong concentration requires low total absorption, so the precoder weights directions that the body absorbs weakly. The MRT precoder places 99.6% of its absorbed power in the eight strongest absorption modes. Skin-aimed ECBF places 35.1% there and the other 64.9% in the weakly absorbed tail (Fig. 5.15c). This mode loading allows the skin-aimed precoder to produce a high local peak while keeping the total absorbed power low. Equation (5.48) divides a local peak by that total, and the weakly absorbed tail keeps the denominator small.

No link precoder reaches the worst case over all precoders. The worst-case contrast increases with the number of directions the scene provides (Section 5.7.6). Thus, a worst-case value is meaningful only together with its retained rank k .

5.7.5 Signal and exposure trade-off

Figure 5.16 shows the Pareto front between received signal power and whole-body absorbed power. Varying the absorbed-power limit moves along this front from MRT through ECBF to the exposure-optimal generalized eigenvalue (GEV) precoder. At half the MRT signal power, the median absorbed power decreases by a factor of 5.42 under LOS and 5.18 under NLOS. Over the limit sweep, the absorbed power never exceeds the absorbed power under MRT. The plotted configuration reaches $6.27\times$ at this point, compared with the $5.42\times$ LOS sweep median. The GEV optimum is many orders of magnitude below the MRT value. The optimum

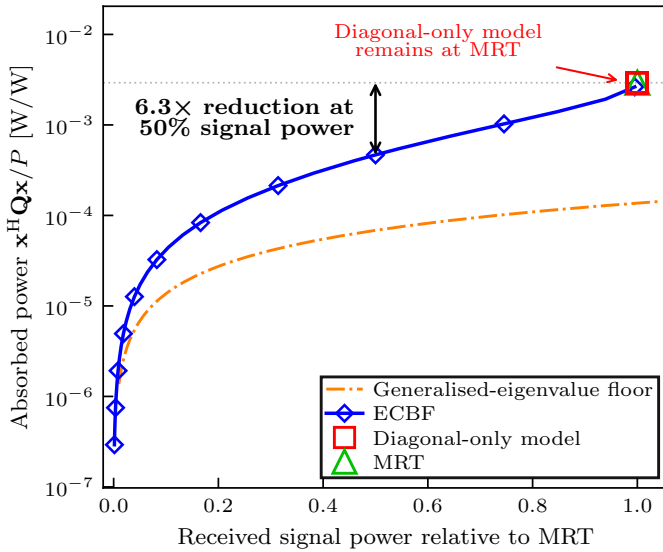


Figure 5.16: The signal–exposure Pareto front for one adult configuration. The ECBF design lowers absorbed power by $6.27\times$ at half the MRT signal power in this configuration. The sweep medians are $5.42\times$ under LOS and $5.18\times$ under NLOS. The front approaches the generalized-eigenvalue floor as the signal power decreases, whereas the diagonal-only model remains at the MRT corner.

reduces absorption to the numerical floor at the cost of eliminating the link entirely.

A scalar-limit design cannot follow this front because the ray-traced operator is not diagonal. The pointwise reduction of Section 5.6.3 permits only a per-element rescaling of the matched filter. Across the four-decade limit sweep, this diagonal-only model remains at the MRT corner. Its absorbed power changes by less than one part in 10^{12} in the plotted replay. Thus, the off-diagonal coupling that the diagonal-only model discards causes the Pareto gain.

The Pareto trade-off also appears spatially as a large change in level with little change in shape. Figure 5.17 shows the absorbed power on an adult body as the absorbed-power limit decreases. The device is at the chest. The MRT precoder produces interference fringes across the whole body. Decreasing the limit to 1% lowers the single-triangle peak by about $78\times$. The lower limit reduces the hot footprint, defined as the surface above half of each panel’s peak, from 849 to 127 cm². The peak-to-mean contrast changes from 8.1 to 10.4. Thus, the design lowers the absorbed-power level without concentrating the remaining deposition. The worst-case precoder has a 1.06 cm² footprint at a contrast of 65.7 and has no link signal.

The exposure reduction along the Pareto front invites two possibilities. At a fixed compliance limit, a link can use the freed absorption margin for more received signal power. At a fixed received signal power, the body absorbs $5.29\times$ less at

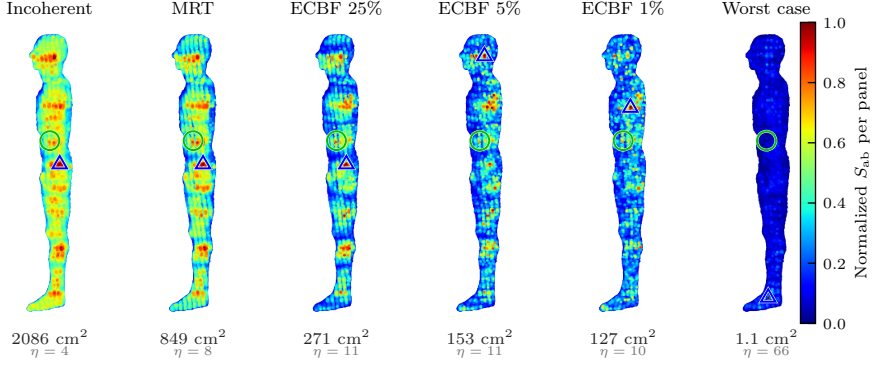


Figure 5.17: Normalized APD on an adult body under LOS at 28 GHz, with the device at the chest. The panels compare incoherent multipath, MRT, ECBF limits, and the worst-case precoder. Each panel is normalized by its own peak. The numbers under each panel give the hot-footprint area (the surface above half that panel's peak) and the peak-to-mean contrast η . A circle marks the served point and a triangle marks the peak.

the population median. This reduction is an ALARA control for the high-EIRP occupational settings of European Union directive 2013/35/EU [50]. A larger array gives stronger control. The median suppression at half the MRT signal power increases from $4.25\times$ at $M = 16$ to $5.35\times$ at $M = 64$ and $6.45\times$ at $M = 256$. At fixed receiver noise and interference, this half-signal point corresponds to a 3.01 dB SNR reduction. Its throughput and bit-error-rate consequences depend on the selected modulation, coding, and link adaptation.

The whole-body constraint does not cover the local restrictions. Above 30 GHz, a compliant design uses the all-patch formulation of Section 5.6.4 to enforce the whole-body, 4 cm^2 , and 1 cm^2 constraints simultaneously. In the campaign, the 1 cm^2 restriction binds first in 10.36% of the high-band ECBF evaluations even though it does so in only 0.73% of the corresponding MRT evaluations.

5.7.6 Worst case over precoders

Section 5.7.4 uses the adversarial maximum over precoders, derived here as a function of retained rank. It lies at the opposite end of the GEV pencil from the exposure-optimal precoder in Section 5.6.4.

Define the single-point operator as $\mathbf{P}(\mathbf{r}) = \tilde{\mathbf{G}}(\mathbf{r})^H \tilde{\mathbf{G}}(\mathbf{r})$. Then $S_{ab}(\mathbf{r}) = \mathbf{x}^H \mathbf{P}(\mathbf{r}) \mathbf{x}$ and $\mathbf{Q} = \int_{\Sigma} \mathbf{P} dA$. Let $\mathbf{Q}_k$ retain the k largest eigenvalues of $\mathbf{Q}$, and let $\mathbf{Q}_k^+$ denote its pseudoinverse. The focusing density $c(\mathbf{r}) = \text{tr}[\mathbf{Q}_k^+ \mathbf{P}(\mathbf{r})]$ integrates to the retained rank:

$$\int_{\Sigma} c(\mathbf{r}) dA = \text{tr}[\mathbf{Q}_k^+ \mathbf{Q}] = k. \quad (5.49)$$

The equality follows because $\mathbf{Q}_k^+$ annihilates the discarded subspace. The total

focusing density is exactly k , regardless of its distribution over the surface. Thus, a precoder that concentrates c at one point reduces it elsewhere.

Restrict the precoder to the k retained directions. Whitening by $\mathbf{Q}_k$ reduces Eq. (5.48) to a Rayleigh quotient. Maximising over the precoder and surface gives

$$\eta_{\max}(k) = |\Sigma| \max_{\mathbf{r} \in \Sigma} \lambda_{\max} \left[\mathbf{Q}_k^{-1/2} \mathbf{P}(\mathbf{r}) \mathbf{Q}_k^{-1/2} \right]. \quad (5.50)$$

The whitened operator has trace $c(\mathbf{r})$ and rank at most three, with one dimension per field component. Thus, its largest eigenvalue lies between $c(\mathbf{r})/3$ and $c(\mathbf{r})$. Equation (5.49) gives c a mean of $k/|\Sigma|$:

$$\frac{1}{3} |\Sigma| \max_{\mathbf{r}} c \leq \eta_{\max}(k) \leq |\Sigma| \max_{\mathbf{r}} c, \quad \eta_{\max}(k) \geq \frac{k}{3}. \quad (5.51)$$

The worst case grows at least linearly with the number of retained directions. Averaging over a local-restriction area cannot increase this maximum because each averaged operator is a convex combination of pointwise operators.

The retained rank affects both the reported value and its physical interpretation. It counts the directions that the scene provides. Thus, the adversarial limit is incomplete without k and depends on the hall. For the same body, a scene with more directions has a larger focusing density and a higher limit.

5.8 Discussion and conclusion

5.8.1 Discussion

The incoherent and coherent formulations describe two levels of one field expansion. Random relative phases suppress the cross-terms and recover the validated surface law. Preserving phase gives the exposure operator required for beamforming. This ordering separates the full-wave validation of the diagonal physics from the additional coherent reduction, whose consistency is evaluated independently in the numerical demonstration. Experimental validation of the coherent operator is part of future work.

The numerical results show why this distinction matters beyond the derivation. Whole-body absorbed power is governed by the surface integral, whereas local exposure is governed by the strongest coherently formed patch. Their ratio depends on both body size and field concentration, so neither restriction can be assumed to bind in advance. Discarding phase leaves total absorption much less affected than the local maximum. Therefore, discarding phase can change both the predicted binding restriction and the location of the hot-spot.

The same distinction limits what can be obtained in closed form. The whole-body operator yields a closed-form signal–exposure trade-off because it is one quadratic form. A local restriction is the maximum of many patchwise quadratic forms. Therefore, the single-active-operator Exposure-Constrained Beamforming (ECBF) result is closed form. The high-band study enforces the complete 1 cm^2

and 4 cm^2 local maps by constraint generation. The general multiuser and all-patch problem has no closed form.

The numerical study also uses a body-free served-link channel even when the device is placed centimetres from the phantom. Therefore, body blockage and scattering can perturb the signal channel used by MRT and ECBF without changing the first-order exposure operator. A body-aware channel sensitivity study is needed to quantify this effect for the closest device placements.

The main limitation of both formulations is the far-field illumination assumption: each path is a single plane wave across the whole body. Indoors, where the source can be less than a meter away, the amplitude and wavefront curvature vary along the body height. Chapter 6 removes this restriction by replacing the far-field paths with Huygens-box wavelets that preserve the spherical wavefront across the body.

The practical consequence is that exposure-aware beamforming becomes an inner-loop step with no full-wave simulation. Because the operator is built from the ray tracer that already estimates the channel, all applicable ICNIRP basic restrictions are evaluated from the same paths. The precoder is re-solved per user as a person moves across the floor. Above 30 GHz the binding restriction is not fixed: wbSAR , the 4 cm^2 average, and the 1 cm^2 average each bind first in part of the campaign. The exposure problem must retain all three. This is a distinction the coherent operator captures and incoherent dosimetry, which superposes powers, cannot. Thus, the method is within reach of 5G and 6G occupational compliance under the ALARA principle, and its incoherent limit is the surface dosimetry law derived and validated in Sections 5.2 and 5.3.

5.8.2 Conclusion

In this chapter, we derived closed-form models for incoherent and coherent absorbed power.

The whole-body absorbed power factors into a flux-weighted Fresnel transmission $\bar{T}(f)$ times a body shape factor A_{ab}/A . Validated four independent ways, it matches FDTD in the mmWave band to within the 7% tissue-dielectric uncertainty. The cost no longer depends on frequency. The f^4 FDTD scaling problem is circumvented by one matrix-vector multiply with positive-part gating, differentiable in antenna position, orientation, beam codebooks, and reconfigurable-intelligent-surface phases. An FDTD simulation campaign that previously required several weeks can now be replaced by a simple ambient-occlusion pass and tissue-property lookup for a given phantom.

The validated surface law supplies the diagonal terms of the coherent formulation. When the cross-path phase terms average to zero, its coherent operator reduces to this incoherent law.

In the coherent part of this chapter, we derived a downlink exposure operator in closed form from the same ray-traced paths that determine the communication channel. The body reduces to a reusable absorption kernel, and the whole-body absorbed power follows in closed form from the path-pair Gram matrix. Exposure-Constrained Beamforming (ECBF) is presented in the downlink as a low-exposure

precoder. An indoor-factory study in FR2 and FR3 evaluated the construction over four phantoms, three square array sizes, eight frequencies from 8 to 100 GHz, two propagation conditions, 16 scene realizations, and nine served-user positions. The MRT and ECBF studies contain 746 496 full-body maps. At half the MRT signal power, the ECBF design suppresses the median whole-body absorbed power by a factor of 5.29, with an interquartile range of 4.43–6.49.

In the next chapter, we apply the resulting multiscale models to broader deployment scenarios and validate them against measurements in controlled and realistic environments.

5.A Grazing-incidence and self-occlusion transitions

The coherent derivation starts from a locally planar Fresnel field and binary visibility. Two transition factors account for grazing incidence and nonlocal self-occlusion. The first is a local Fock factor for the body's own terminator. The second is a nonlocal gate for an occlusion boundary formed by another body part. Before summation, each path field is multiplied by both factors. This per-path multiplication is linear. Hence, the coherent cross-terms and the element-space absorption operator have the form derived in the main text.

The leading surface field is the locally planar Fresnel response. The Fock and edge terms are high-frequency diffraction corrections [45, 51–53].

For path n at surface point $\mathbf{r}$, define the incidence cosine

$$\mu_n(\mathbf{r}) = \hat{\mathbf{n}}(\mathbf{r}) \cdot (-\hat{\mathbf{k}}_n). \quad (5.52)$$

The incident TE and TM directions are $\hat{\mathbf{e}}_{s,n}$ and $\hat{\mathbf{e}}_{p,n}$, respectively. The transmitted TE direction remains $\hat{\mathbf{e}}_{s,n}$. Applying Snell's law and Maxwell transversality, the transmitted TM direction is

$$\hat{\mathbf{e}}'_{p,n} = \frac{\xi_n \hat{\mathbf{t}}_n + \sqrt{1 - \mu_n^2} \hat{\mathbf{n}}}{\tilde{n}}, \quad \xi_n = \sqrt{\tilde{n}^2 - 1 + \mu_n^2}, \quad \text{Re}(\xi_n) > 0, \quad (5.53)$$

where $\hat{\mathbf{t}}_n$ is the unit projection of the incident ray onto the tangent plane. The complex direction is not unit-normalized.

The local grazing transition depends on the radius of curvature in the incidence plane. Let $\kappa_1 \geq \kappa_2$ be the principal curvatures and $\mathbf{e}_1, \mathbf{e}_2$ their orthonormal directions in the tangent plane. These curvatures and directions are obtained from a local quadratic fit to the surface. For nonnormal incidence,

$$\hat{\mathbf{t}}_n = \frac{\hat{\mathbf{k}}_n - (\hat{\mathbf{k}}_n \cdot \hat{\mathbf{n}}) \hat{\mathbf{n}}}{\|\hat{\mathbf{k}}_n - (\hat{\mathbf{k}}_n \cdot \hat{\mathbf{n}}) \hat{\mathbf{n}}\|}. \quad (5.54)$$

If φ_n is the angle between $\hat{\mathbf{t}}_n$ and $\mathbf{e}_1$, Euler's formula for the normal curvature is

$$\kappa_{t,n} = \kappa_1 \cos^2 \varphi_n + \kappa_2 \sin^2 \varphi_n, \quad R_{F,n} = \frac{1}{\max(\kappa_{t,n}, \kappa_{\min})}. \quad (5.55)$$

Here $\kappa_{\min} = 10^{-6} \text{ m}^{-1}$ when $\kappa_{t,n} \leq 0$. At normal incidence, where the tangent projection is undefined, $\kappa_{t,n} = \kappa_1$.

The local Fock coordinate is determined by $R_{F,n}$. The signed angle from the terminator is

$$\theta_n = \arcsin \mu_n, \quad \theta_n > 0 \text{ lit}, \quad \theta_n < 0 \text{ shadowed}, \quad (5.56)$$

and the corresponding detour coordinate is

$$m_{F,n} = \left(\frac{kR_{F,n}}{2} \right)^{1/3}, \quad \xi_{F,n} = m_{F,n} \theta_n. \quad (5.57)$$

The smooth-body transition has angular width $O[(kR_{F,n})^{-1/3}]$ [45, 51]. The incidence-plane radius differs from the mean-curvature surrogate. For a circular cylinder illuminated perpendicular to its axis, $R_{F,n} = R$, whereas the mean-curvature surrogate $2/(\kappa_1 + \kappa_2)$ equals $2R$. The transition widths differ by $2^{1/3}$. For a sphere, both radii equal R .

For $u \in \{s, h\}$, where s and h denote the *soft* (TE) and *hard* (TM) Fock channels, let $g_u^{(P)}$ denote the complex field gate formed from P poles,

$$g_u^{(P)}(\xi) = \Phi(\xi) + [1 - \Phi(\xi)] C_F \sum_{p=1}^P A_{p,u} \exp[i\nu_{p,u} s_-(\xi)], \quad (5.58)$$

where

$$\Phi(\xi) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\xi}{\sqrt{2}} \right) \right], \quad (5.59)$$

$$s_-(\xi) = -\frac{1}{b} \log(1 + e^{-b\xi}), \quad b = 8. \quad (5.60)$$

For $\xi < 0$, $s_-(\xi) \simeq \xi$. For $\xi > 0$, $s_-(\xi) \simeq 0$ and $1 - \Phi(\xi) \simeq 0$, so the residue contribution vanishes. For the local gate, $P = 3$. The scale C_F is set by the perfect-conductor hard polarization value $|g_h^{(3)}(0)|^2 = 0.488$ at the terminator. The same C_F is retained for both pole truncations used below.

The pole and residue data depend on the polarization and the surface boundary condition. We first define both channels for a perfect conductor. The soft and hard pole magnitudes are determined by the Airy and Airy-derivative zeros,

$$\begin{aligned} \text{Ai}(-q_{p,s}) &= 0, & q_{1,s} &= 2.338, \\ \text{Ai}'(-q_{p,h}) &= 0, & q_{1,h} &= 1.019. \end{aligned} \quad (5.61)$$

The corresponding residue magnitudes are

$$A_{p,s} = \left| \frac{1}{\text{Ai}'(a_p)^2} \right|, \quad A_{p,h} = \left| \frac{1}{a_p' \text{Ai}(a_p')^2} \right|, \quad (5.62)$$

where $a_p = -q_{p,s} < 0$ and $a_p' = -q_{p,h} < 0$ are the corresponding signed zeros. For real perfect-conductor roots, $\nu_{p,u} = q_{p,u} e^{-i\pi/3}$. The shadow power then decays as $\exp[-\sqrt{3}q_{1,u}|\xi|]$.

For lossy skin, only the hard channel differs. The soft-channel poles and residues remain those of the perfect conductor. With surface impedance $\zeta = 1/\tilde{n}$, the hard-channel poles satisfy

$$\text{Ai}'(t) - q_F \text{Ai}(t) = 0, \quad q_{p,h} = -t_p. \quad (5.63)$$

The parameter q_F is obtained from the dominant Leontovich cylinder pole. Let ν_* denote this pole for a representative electrical radius kR . Then

$$t_* = -\frac{\nu_* - kR}{(kR/2)^{1/3} e^{i\pi/3}}, \quad q_F = \frac{\text{Ai}'(t_*)}{\text{Ai}(t_*)}. \quad (5.64)$$

With this q_F , $t = t_*$ satisfies Eq. (5.63). The tissue convention is $\tilde{n} = n - i\kappa$ with time dependence $e^{+i\omega t}$. The reference cylinder solution has time dependence $e^{-i\omega t}$, so the hard exponent is $\nu_{p,h} = q_{p,h}^* e^{-i\pi/3}$. The conjugation leaves the real perfect-conductor roots unchanged. The resulting sign corresponds to decay for passive tissue.

The lossy hard-channel residue magnitudes associated with the shifted roots $t_{p,h} = -q_{p,h}$ are

$$A_{p,h}^{\text{lossy}} = \left| \frac{1}{t_{p,h} \text{Ai}(t_{p,h})^2} \right|. \quad (5.65)$$

The mapping is exact for the dominant hard root. The higher shifted roots and residue amplitudes are evaluated with the leading Fock approximation. The directional radius $R_{F,n}$ is specific to each surface point and path. One representative hard-channel impedance parameter is used for each body, frequency, and ray set.

The local Fock correction is smooth and complex near grazing incidence on the illuminated side of the terminator. The Heaviside factor $H(\mu_n)$ equals one for $\mu_n > 0$ and zero otherwise. Multiplication by $H(\mu_n)$ removes the direct field for triangle-path pairs with $\mu_n \leq 0$ before multiplication by the Fock factor. No coherent creeping-wave field around the terminator and into the geometric shadow is included.

Nonlocal self-occlusion occurs when one body part blocks another. For surface point $\mathbf{r}$, let $B(\mathbf{r})$ be the blocked set on the unit direction sphere and $\partial B(\mathbf{r})$ its occlusion horizon. With source direction $\boldsymbol{\omega}_n = -\hat{\mathbf{k}}_n$, define the signed angular distance to this horizon as

$$c_n(\mathbf{r}) = s_n \inf_{\mathbf{b} \in \partial B(\mathbf{r})} \arccos(\boldsymbol{\omega}_n \cdot \mathbf{b}), \quad s_n = \begin{cases} +1, & \boldsymbol{\omega}_n \notin B(\mathbf{r}), \\ -1, & \boldsymbol{\omega}_n \in B(\mathbf{r}). \end{cases} \quad (5.66)$$

Positive c_n denotes a visible direction and negative c_n a blocked direction. The local terminator angle θ_n is the same construction with the tangent-plane terminator as the boundary.

For numerical evaluation, mesh ray casting tabulates a discrete approximation of c_n on an octahedral direction grid. The same table contains the mean hit distance d_2 and mean in-plane occluder radius R_{occ} over the shadowed grid directions of each active triangle. Hence, c_n depends on the arrival direction, whereas d_2 and R_{occ} do not.

For the nonlocal correction, the smooth-body and sharp-edge transition scales are compared. For a smooth convex occluder,

$$\sigma_F = 2^{5/6} (kR_{\text{occ}})^{-1/3}, \quad \xi_d = \left(\frac{kR_{\text{occ}}}{2} \right)^{1/3} c_n. \quad (5.67)$$

For a sharp edge, the far-field Fresnel scale is

$$\sigma_{\text{ke}} = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{\lambda}{d_2}}, \quad V_{\text{ke}} = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{c_n}{\sigma_{\text{ke}}} \right) \right]. \quad (5.68)$$

The smooth-body scale has $k^{-1/3}$ dependence, whereas the sharp-edge scale has $k^{-1/2}$ dependence. The wider transition is used as a conservative model-composition rule.

The nonlocal correction is independent of incident polarization. Its smooth-body power is the mean of the soft- and hard-channel powers. With $P = 5$ in Eq. (5.58),

$$G_F(c_n) = \frac{1}{2} |g_s^{(5)}(\xi_d)|^2 + \frac{1}{2} |g_h^{(5)}(\xi_d)|^2. \quad (5.69)$$

The selected power gate and its field amplitude are

$$G_d(c_n) = \begin{cases} G_F(c_n), & \sigma_F \geq \sigma_{\text{ke}}, \\ V_{\text{ke}}(c_n), & \sigma_F < \sigma_{\text{ke}}, \end{cases} \quad a_{d,n} = \sqrt{\max(G_d, 0)}. \quad (5.70)$$

The field amplitude is the nonnegative square root of the power gate. No additional nonlocal binary-occlusion mask is applied, since both terms describe the same occlusion boundary. The factor $a_{d,n}$ is an amplitude-only correction, without the phase or path geometry of a separate diffracted ray.

The complete surface field can now be assembled. The local soft and hard gates are polarization-specific, whereas $a_{d,n}$ is common to both components. Let $t_{s,n}$ and $t_{p,n}$ be the electric-field Fresnel transmission coefficients. The modified per-path surface response is

$$\mathbf{F}_n^{\text{surf}}(\mathbf{r})\psi_n = a_{d,n}(\mathbf{r})H(\mu_n)[g_s^{(3)}(\xi_{F,n})t_{s,n}(\hat{\mathbf{e}}_{s,n}^T\psi_n)\hat{\mathbf{e}}_{s,n} + g_h^{(3)}(\xi_{F,n})t_{p,n}(\hat{\mathbf{e}}_{p,n}^T\psi_n)\hat{\mathbf{e}}'_{p,n}]. \quad (5.71)$$

Deep in the lit region, $g_s^{(3)}$ and $g_h^{(3)}$ tend to one. With $a_{d,n} = 1$, the bare Fresnel field is recovered from Eq. (5.71).

For the depth reduction, the mean-depth rank-one approximation is $\Gamma_{nn'} \approx e^{-i(\beta_{n'} - \beta_n)\delta}$. The corresponding per-path field is

$$\tilde{\psi}_n^{\text{surf}}(\mathbf{r}) = \sqrt{\frac{\sigma}{4\alpha_n}} e^{-i\beta_n\delta} \mathbf{F}_n^{\text{surf}}(\mathbf{r})\psi_n. \quad (5.72)$$

Here $\tilde{n}$, σ , α_n , β_n , and the mean absorption depth δ are the half-space tissue parameters.

All factors in Eq. (5.72) depend on the body, path, frequency, and tissue, but not on the precoder. The surface channel $\tilde{\mathbf{G}}_{\text{surf}}(\mathbf{r})$ therefore remains linear in the array excitation. The absorbed power is

$$P_{\text{abs}}(\mathbf{x}) = \int_{\Sigma} \|\tilde{\mathbf{G}}_{\text{surf}}(\mathbf{r})\mathbf{x}\|^2 dA = \mathbf{x}^H \mathbf{Q}_{\text{surf}} \mathbf{x}, \quad (5.73)$$

with

$$\mathbf{Q}_{\text{surf}} = \int_{\Sigma} \tilde{\mathbf{G}}_{\text{surf}}^H(\mathbf{r})\tilde{\mathbf{G}}_{\text{surf}}(\mathbf{r}) dA \succeq 0. \quad (5.74)$$

The Gram form in Eq. (5.74) is Hermitian positive semidefinite by construction. The corresponding local operator is obtained by replacing Σ with a nonnegative normalized averaging weight; the surface response and factorization are unchanged.

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6

Experimental Validation and City-Scale Exposure

“I don’t see how a world that makes such wonderful things could be bad.”

— Ariel, *The Little Mermaid*

This chapter is adapted from:

- Robin Wydaeghe, Arno Moerman, Olivier Caytan, Sergei Shikhantsov, Emmeric Tanghe, Günter Vermeeren, Hendrik Rogier, Sam Lemey, Piet Demeester, and Wout Joseph, “New hybrid ray-tracing/FDTD for EMF exposure in 6G networks using semantically classified Google Earth photogrammetry with measurement validation,” in *Proc. European Conference on Antennas and Propagation (EuCAP)*, Glasgow, U.K., Mar. 2024.
- Robin Wydaeghe, Olivier Caytan, Sergei Shikhantsov, Emmeric Tanghe, Günter Vermeeren, Hendrik Rogier, Sam Lemey, Piet Demeester, and Wout Joseph, “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. European Conference on Antennas and Propagation (EuCAP)*, Stockholm, Sweden, Mar.–Apr. 2025.
- Robin Wydaeghe, Olivier Caytan, Günter Vermeeren, Hendrik Rogier, Sam Lemey, Emmeric Tanghe, and Wout Joseph, “Digital twin calibrated from phaseless 28 GHz measurement scans for indoor exposure assessment,” manuscript submitted to *IEEE Antennas and Wireless Propagation Letters*.

- Robin Wydaeghe, Günter Vermeeren, Emmeric Tanghe, and Wout Joseph, “Human-centric 6G RF-EMF exposure with AI-assisted digital twins in ten cities,” manuscript submitted to *IEEE Open Journal of the Communications Society*.

The preceding chapters replaced both the full-wave propagation step (Chapter 3) and the full-wave exposure step (Chapter 5) with faster alternatives whose accuracy was verified against numerical references. This chapter now validates those models against physical measurements and then applies the resulting method across ten cities. The first part validates the hybrid ray-tracing pipeline in a controlled anechoic environment at 26 GHz and a realistic indoor environment at 28 GHz. In the indoor case, a Huygens box around the phantom couples the calibrated twin’s field to the closed-form surface law of Chapter 5. The second part then combines the closed-form surface exposure law with an adjoint ray tracer whose cost is independent of the number of sources, making city-scale studies with dense deployments tractable. We apply this combination to ten street-level routes across three continents at 15 GHz. The ten-route calculation takes 314 s on a single GPU.

6.1 Introduction

The hybrid ray-tracing/FDTD pipeline developed in Chapters 3 and 4 predicts EMF exposure along a user path by decomposing the problem into a propagation step and an exposure step. The propagation step produces complex field amplitudes at the location of the UE. The exposure step uses these amplitudes to compute SAR and APD on an anatomical phantom. Both steps contain physical approximations (specular-only ray tracing, far-field hybridization, surface-only absorption), and each approximation must be verified against measurements before the pipeline can be trusted for compliance assessment.

Measurement-based validation of mmWave exposure models is scarce. Robotic scanning with a calibrated probe at 26–28 GHz [FR2] requires sub-millimeter positioning, total measurement times of tens of hours, and a static environment throughout. Phase information is lost during detection, so any comparison with a simulation is limited to magnitude patterns. The rich multipath environment at mmWave frequencies makes the interference pattern sensitive to millimeter-level misalignments between the physical setup and its digital twin.

This chapter presents two experiments that validate the pipeline at increasing levels of complexity. First, a free-space measurement in an anechoic room at 26 GHz validates the hybridization procedure in isolation, with no multipath and a fully controlled geometry (Section 6.2). Second, a realistic indoor measurement at 28 GHz in a stairwell evaluates ray tracing, material assignment, and exposure computation together in the presence of walls, floor, ceiling, and a metal railing (Sections 6.3 and 6.3.4). The two experiments use the same probe hardware and positioning robot, and compare measured field magnitudes with simulated fields at the same spatial locations [1–3]. In the indoor experiment, a physically

parameterized digital twin is calibrated on the magnitude data and validated with held-out planes.

6.2 Free-space measurement validation

The first validation step isolates the hybridization procedure from environmental uncertainty. A 16-element DMaMIMO antenna system creates a beamformed hot-spot in an anechoic room at 26 GHz. The magnitude of the electric field is scanned over a two-dimensional plane through the hot-spot and compared with the hybridization output described in Chapter 4.

6.2.1 Measurement configuration

Four sets of 4×1 air-filled substrate-integrated-waveguide antenna elements [4] are mounted on a glass-fibre pole at heights $z = -0.52, -0.15, +0.15$, and $+0.52$ m relative to the scan-plane centre. Each set is fed through a Butler matrix [5] that selects one of four beam directions ($\pm 14^\circ, \pm 44^\circ$). The beam directions are chosen so that all four sets point toward the scan-plane centre, reproducing a distributed-antenna beamforming geometry.

The radio-frequency source at 26 GHz is split into four paths with passive power splitters. Three manual phase shifters (mechanical path-length extenders, $11^\circ/\text{GHz}$) are inserted on three of the four paths. The maximum phase range is $3\pi/4$ per shifter. The measured output amplitudes of the four sets are 0.022, 0.070, 0.042, and 0.035 V/m (from the lowest set upward), a spread of 1 to 2 dB caused by the splitter chain. The phase shifters are adjusted so that the interference pattern between each pair of sets has a maximum at the scan-plane centre. This is a one-time calibration: once the phases are set, the hot-spot position is fixed for all subsequent measurements. By superposition, all four sets then interfere constructively at that point, replicating active reciprocity-based beamforming.

The receiving probe is a Narda FR2 electric-field probe [6] (26.5–29.5 GHz bandwidth) mounted on a Velmex three-axis positioning system. The probe measures the magnitude of the electric-field component along its longitudinal axis, which is oriented parallel to the scanning plane. The signal is internally downconverted to below 6 GHz and read by a Narda SRM-3006 selective radiation meter. The two-dimensional scan covers 50×50 cm ($\approx 44\lambda \times 44\lambda$) at a resolution of 3.33 mm (0.29 λ). The pole carrying the antenna sets is placed at 62 cm from the scanning plane. The total measurement time is 50 hours. The measured SNR ranges from 12 to 28 dB across the scan.

6.2.2 Hybridization

The validation simulation replicates the physical setup in free space. The position and orientation of each antenna set and the probe are modelled from laser-aligned distance measurements with millimetre precision. A full-wave simulation of the

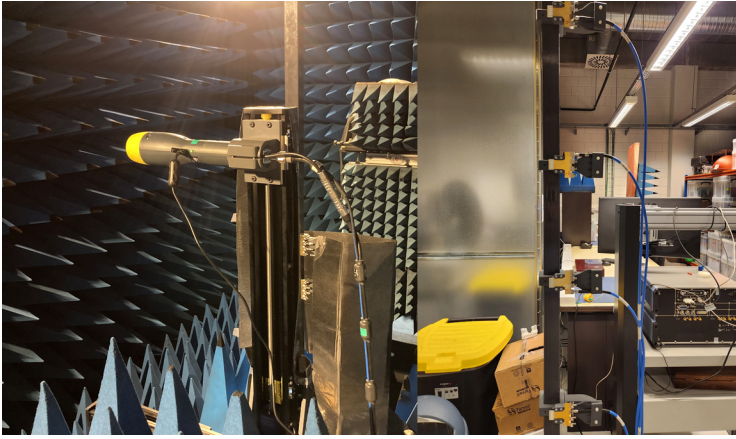


Figure 6.1: Measurement setup in the anechoic room. Left: the Narda FR2 probe on the three-axis positioner. Right: the four 4×1 antenna sets mounted on the glass-fibre pole, with the power splitter and phase shifters visible behind the absorber wall.

4×1 set (including the Butler matrix) runs in CST Microwave Studio [7] to obtain far-field radiation patterns for each beam direction. The Fraunhofer distance of a single 4×1 set is 14.2 cm. Including the Butler matrix, it increases to 95.2 cm. The source-to-centre distances are approximately 63.8 cm for the inner sets and 80.9 cm for the outer sets. At these distances, we assume that radiation from the array dominates the external field.

Inter-element coupling between the four sets, separated by about 30 wavelengths on the pole, is neglected. The total field on the scanning grid is the coherent sum of four spherically expanding waves, one per set, each with the CST-computed far-field pattern of the driven beam direction. The simulation grid has ten times the resolution of the measurement grid. The same summation procedure underlies the hybridization component of the pipeline (Chapter 4). Therefore, the measurement validates this component directly.

The channel is precoded with MRT, and the measured per-set amplitudes are applied as weights. The absolute value of the electric-field component parallel to the probe axis is evaluated on the same two-dimensional grid as the measurement.

6.2.3 Results

Fig. 6.2 compares the measured and simulated electric-field magnitude over the scanning plane. Five features characterize the measured pattern. The first four also appear in the simulation. First, a large-scale ellipsoidal region of elevated field, caused by the alignment of the four main beams onto the same area, spans several wavelengths. Second, adjacent wavelength-sized side lobes appear where a subset of beams interfere constructively. Third, a small-scale constructive peak at the

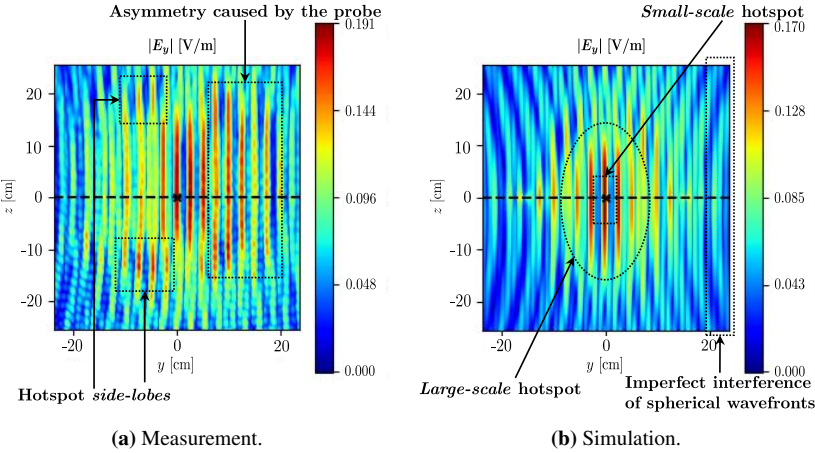


Figure 6.2: Electric-field magnitude in the scanning plane of the anechoic-room hot-spot from the 16-element DMaMIMO system at 26 GHz. The dashed line marks the one-dimensional slice evaluated in Table 6.1.

Table 6.1: Free-space validation: measurement versus simulation along the one-dimensional slice through the scan-plane centre ($z = 0$ cm).

Metric	Measurement	Simulation
Peak $ E $ (V/m)	0.19	0.17
FWHM of central peak (cm)	0.93	0.94
Normalised mean abs. error (NMAE)	$17\% \pm 10\%$ (0.65 dB)	
Mean matched-peak height difference	6.5%	
Mean matched-peak position difference	0.26%	

centre of the hot-spot, where the wavefronts from all 16 elements add in phase, has the highest amplitude. Fourth, vertical lines of constructive interference appear outside the hot-spot, becoming more curved and weaker with distance from the centre. Fifth, the higher field to the right of the centre is attributed to scattering from the 48.5 cm Narda probe. The simulation omits the probe, so it does not reproduce this asymmetry.

Table 6.1 summarizes the one-dimensional comparison along the horizontal slice at $z = 0$ cm (dashed line in Fig. 6.2). The normalised mean absolute error (NMAE) between measurement and simulation is $17\% \pm 10\%$, or 0.65 dB. Fig. 6.3 shows the slice in detail. The measurement and simulation peaks are matched by hand: each measured interference peak is paired with its nearest simulated counterpart. The average height difference between matched peaks is 6.5% (with a spread of $\pm 28\%$ over the full slice, tightening to $\pm 5\%$ within the hot-spot). The positional mismatch is 0.26%, limited by the 3.33 mm scan-grid resolution.

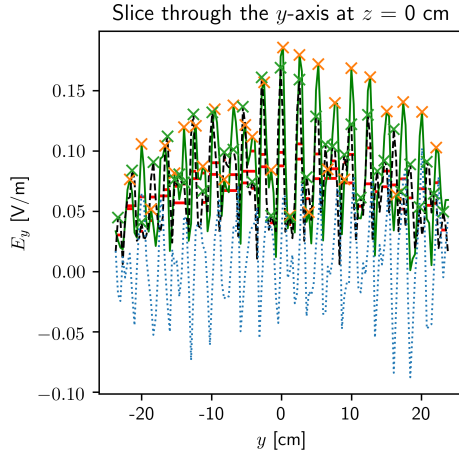


Figure 6.3: One-dimensional slice through the scan-plane centre ($z = 0$ cm): measured (green) and simulated (black) electric-field magnitude. Identified peaks are marked with crosses. The FWHM of each peak is shown with a horizontal bar.

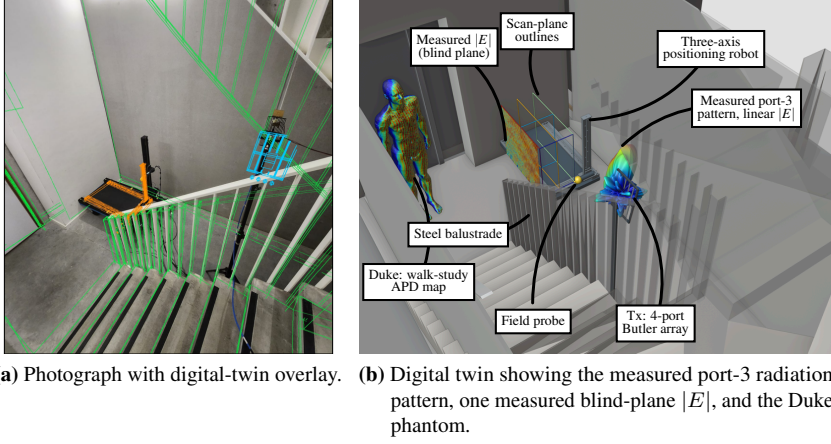
The main source of disagreement is the probe-induced asymmetry (feature 5 above): the measurement has higher fields to the right of centre where scattered energy from the probe accumulates, whereas the simulation is symmetric. Within the hot-spot core, the agreement is within the measurement uncertainty of the Narda probe.

6.3 Realistic indoor measurement and digital twin calibration

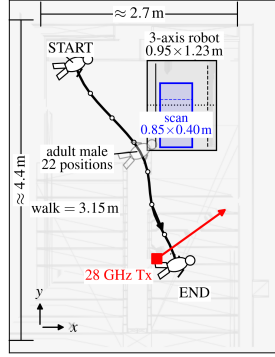
The free-space measurement validates the hybridization step with a 17% NMAE on the horizontal slice. We next evaluate the pipeline with ray tracing in a room where walls, floor, and ceiling have different materials and where multipath is present. In a realistic environment the digital twin must also reproduce material reflections, antenna placement, and scan-frame alignment. Phase information is unavailable, so the comparison is limited to magnitude patterns.

6.3.1 Measurement configuration

The environment is a stairwell at Ghent University with smooth concrete walls, a door, and a U-shaped metal stair railing (Fig. 6.4). The stairwell is a realistic indoor setting without movable clutter. A single 4×1 antenna element set, identical to those used in the free-space experiment, is mounted on a pole at a height of 1.68 m, tilting downward by 11.5° . The Butler matrix [5] selects the -14° beam direction on port 3, directing the beam toward the measurement volume [4].



(a) Photograph with digital-twin overlay. (b) Digital twin showing the measured port-3 radiation pattern, one measured blind-plane $|E|$, and the Duke phantom.



(c) Top view of the 3.2 m exposure walk.

Figure 6.4: Configuration of the 28 GHz indoor measurement and its digital twin. (a) The three-axis robot scans five planes in the stairwell. (b) The digital twin contains the measured antenna pattern, room geometry, measurement plane, and Duke phantom. (c) The adult male phantom walks 3.2 m through 22 positions from the marked start to end, past the robot and scan volume toward the transmitter.

The receiving side uses the same Narda FR2 probe [6] at 28 GHz, now mounted on a three-axis Velmex robot. The probe axis is aligned with the y -direction (parallel to the door). The robot traces a snake-like path through the scan volume, measuring field values continuously. This operating mode shifts the measurement bottleneck from the probe response time (as in the anechoic measurement) to the actuator speed, and makes the resolution continuous along one axis of the sweep while discrete along the other two axes.

The scanned domain measures $85 \times 40 \times 70$ cm. At a discrete-axis resolution of $\lambda/4$, five planar slices are measured: two yz -planes at $x = 0$ and 40 cm, and

three xz -planes at $y = 0, 20$, and 40 cm. The five scans take a total of 31 hours.

The measurements have two systematic errors. The first is a multiplicative instrument response of the spectrum analyser, which modulates the measured amplitude along each continuous sweep. The second is a timing offset between the robot position and the recorded field value, which shifts the pattern by a fraction of a wavelength depending on the sweep direction. Both errors are corrected before any comparison with the simulation.

One plane ($x = 40$ cm) has low repeatability: the correlation between two sweep directions at their intersection is $r \leq 0.32$, compared with ≈ 0.9 for the remaining planes. This plane is excluded from all comparisons.

6.3.2 Digital twin and calibration

The room geometry comes from an accurate architectural model, which is converted from CAD to a surface mesh. We verify that the model distances match distance measurements in the room. The antenna, robot, and probe positions are measured and placed in the digital twin. This is an offline model of the stairwell, with pose and material parameters calibrated from the field scans.

The ray tracer uses single-bounce specular paths. Material classes (concrete, masonry, plaster, metal) have permittivity and conductivity values constrained to the ranges in [8]. The stair railing is included as flat metal, but its grating-like diffraction response falls outside the specular model. The antenna radiation pattern is obtained from an anechoic-chamber measurement of the driven port [4]. Movable equipment (the robot itself, cables) is not modelled.

The digital twin has approximately ten continuous pose parameters (antenna position and orientation, scan-frame alignment, probe offset, pattern roll) and eight material parameters (permittivity and conductivity for each of four wall classes). All parameters are constrained to physically realistic ranges.

The power delivered to the antenna is not measured directly because losses in the source chain were not characterized. All comparison metrics are therefore scale-invariant. For exposure, the simulated field is scaled to the absolute probe amplitude on the training planes. Three correlation metrics measure agreement at different spatial scales. First, the measured and predicted field magnitudes are smoothed with a Gaussian kernel whose standard deviation is 2λ . Their correlation measures the broad spatial power distribution. Second, the beat spectrum is the mean magnitude spectrum of the scan rows from 0.35 to 2.05 cycles per wavelength. It is shift-invariant and tests whether the model reproduces the main interference spacings. Third, raw Pearson correlation tests point-by-point agreement and is sensitive to sub-wavelength positioning errors.

The parameter search uses the smoothed-field metric, because raw correlation has a local optimum at every $\lambda/4$ of position error. The final model selection uses the beat spectrum, which tests interference structure independently of absolute position.

The model is selected using only the planes it was fitted on (the training planes). Each remaining plane is set aside as a test plane and used only to check the selection,

Table 6.2: Blind validation on rotated leave-one-plane-out planes. Pearson correlations are model versus measurement on each held-out plane.

Held-out plane	Smoothed $ E $	Beat spectrum	Raw
$x=0$	+0.19	+0.57	+0.08
$y=0$	+0.53	+0.55	+0.13
$y=20$ cm	+0.67	+0.75	+0.20
$y=40$ cm	+0.56	+0.79	+0.17
Mean	+0.49	+0.66	+0.15

never to drive it. When the selection was instead based on the test planes, the best candidates had negative correlation on the training planes, a sign that the model had fitted noise rather than physical structure. In a synthetic test with known ground truth, the same procedure returned the correct answer as the top candidate out of 41 tested [2].

6.3.3 Blind validation results

Each of the four scored measurement planes is held out in turn (leave-one-plane-out cross-validation). For each rotation, the model is selected by maximizing the sum of smoothed-field and beat-spectrum correlations on the three remaining training planes.

Table 6.2 reports the validation scores. Beat-spectrum correlations range from +0.55 to +0.79 across the four held-out planes. Smoothed-field correlations range from +0.19 to +0.67 (mean +0.49). Raw correlations are positive on every held-out plane but modest (+0.08 to +0.20), reflecting the sub-wavelength sensitivity of point-by-point comparison.

Fig. 6.5b shows that the correlation between model and measurement grows monotonically with the spatial averaging scale, rising from +0.17 (raw) to +0.57 at a Gaussian standard deviation of 2λ and +0.65 at 4λ on the $y=40$ cm blind plane. The training-plane mean follows the same trend at higher values. The shaded band marks the ICNIRP 1–4 cm² averaging apertures. Because the exposure limits are defined on spatially averaged quantities, the digital twin predicts the spatially averaged quantities used for exposure compliance.

Fig. 6.5c compares the measured and simulated beat spectra on the $y=40$ cm blind plane. The model reproduces the strongest interference spacings. The measured field has two to three times the fine-scale variation of the model, consistent with interference from non-specular paths (diffraction, diffuse scattering) that the single-bounce specular model does not include.

Adding second-bounce specular paths and diffuse scattering both increase the smoothed-field correlation but reduce the interference-spacing agreement to near zero. Near-perfect electric conductor (PEC) material parameters produce the opposite effect: interference-spacing metrics improve, but the smoothed-field

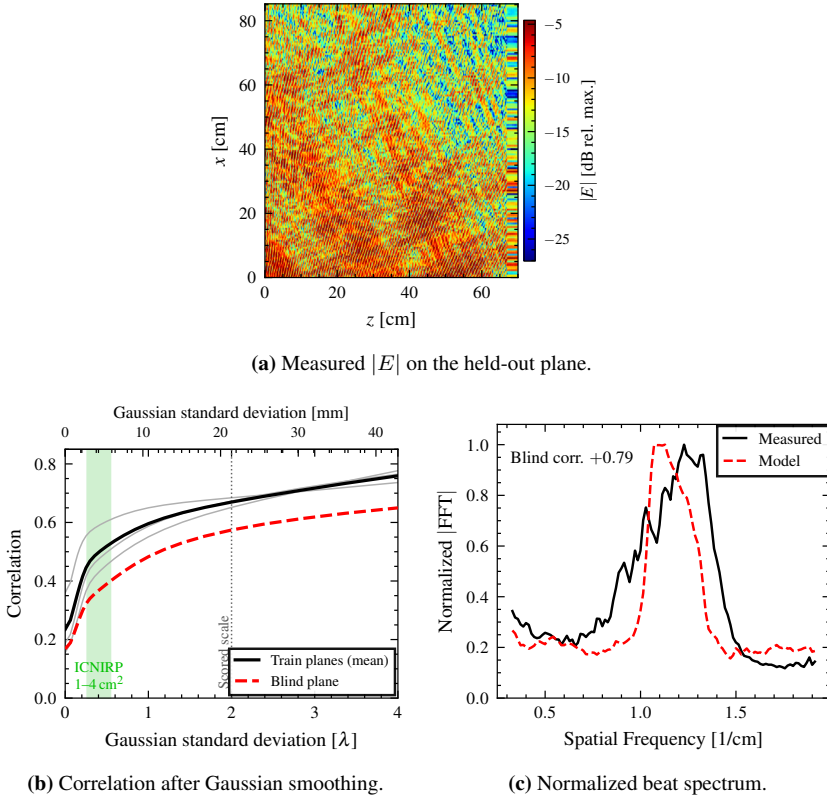


Figure 6.5: Blind validation on the held-out $y=40$ cm plane. (a) Measured field magnitude in dB, normalized to its maximum. (b) Pearson correlation after Gaussian smoothing. Black is the mean of the training planes and red is the held-out plane. (c) Measured and predicted beat spectra, each normalized to its maximum.

correlation degrades. These observations show that the held-out beat-spectrum correlations in Table 6.2 reflect genuine interference agreement, not accidental parameter compensation.

6.3.3.1 Largest error source

On every scan plane, the two-dimensional beat spectrum shows one measured interference pair that is not in the model. A two-ray arrival model places the missing scatterer at elevation $+26^\circ$ to $+30^\circ$ and azimuth $\approx \pm 95^\circ$ from the antenna boresight. This direction points to the stair railing (Fig. 6.4c), a periodic metal grating with a pitch of about 9.3λ at 28 GHz. The single-bounce specular model used here omits the railing's grating-like scattering response.

6.3.4 Exposure assessment

The calibrated digital twin provides a full complex electric field (magnitude and phase from the ray tracer) over the walkable area of the room. At 28 GHz the skin depth in tissue is a fraction of a millimetre [9], so absorption is a surface phenomenon. This is the regime where the closed-form surface exposure law developed in Chapter 5 applies. However, that law assumes far-field illumination: each path is a plane wave with a single complex amplitude and a linear phase across the whole body. In the stairwell the antenna is 0.5–3 m from the phantom, so the amplitude and wavefront curvature vary along the 1.8 m body height and the plane-wave-across-the-body assumption does not hold.

Therefore, we enclose the phantom in a rectangular Huygens box with 10 cm separation on five sides (no separation at the floor plane). At each of 22 walk positions, the ray tracer exports the per-path Jones vectors and directions on the six box planes at $\leq \lambda/2$ sampling. The tangential electric and magnetic fields on the box follow from $\mathbf{H} = (1/\eta_0) \hat{\mathbf{k}} \times \mathbf{E}$ per path, summed over all paths. By Love’s equivalence theorem, equivalent electric and magnetic surface currents on the box radiate the interior incident field through free-space Green functions:

$$\mathbf{E}_{\text{inc}}(\mathbf{r}) \approx \sum_m \mathbf{a}_m(\mathbf{r}) \frac{e^{-jk_0 R_m}}{4\pi R_m}, \quad (6.1)$$

where $R_m = |\mathbf{r} - \mathbf{r}'_m|$ is the distance from box sample m to the body-surface point $\mathbf{r}$, and the vector amplitude is

$$\mathbf{a}_m(\mathbf{r}) = jk_0 \Delta S_m [-\eta_0 (\hat{\mathbf{n}}' \times \mathbf{H})_m + (\hat{\mathbf{n}}' \times \mathbf{E})_m \times \hat{\mathbf{R}}_m + (\hat{\mathbf{n}}' \cdot \mathbf{E})_m \hat{\mathbf{R}}_m]. \quad (6.2)$$

Each term in the sum is a wavelet arriving from direction $\hat{\mathbf{k}}_m(\mathbf{r}) = \hat{\mathbf{R}}_m$ with a point-dependent amplitude and polarisation. At each body-surface point, the per-path transmitted field of Chapter 5 (Eq. (5.28)) is evaluated with the wavelet replacing the plane-wave excitation: the global direction $\hat{\mathbf{k}}_n$ is replaced by the point-dependent $\hat{\mathbf{k}}_m(\mathbf{r})$, and the spherical wavefront enters through the $1/R_m$ decay. The Fresnel transmission coefficients, the Heaviside back-face condition, the self-occlusion check (now a finite segment from the box sample to the surface point), the Fock transition near grazing, the depth absorption, and the coherent sum are all applied as in Chapter 5. The box separation (≥ 5 cm at 28 GHz, i.e. $k_0 R \gtrsim 30$) ensures that the radiating-term approximation in (6.1) is accurate.

We compute SAR_{wb} and $\text{APD}_{4 \text{ cm}^2}$ on a posed Duke anatomical phantom [10] using this Huygens-box coupling with directional self-shadowing. The 4 cm^2 averaging area is the ICNIRP 2020 basic restriction [11] for local exposure from 6 to 300 GHz. We also report APD over 1 cm^2 as an informative quantity: the 1 cm^2 criterion applies above 30 GHz, where its limit is twice the 4 cm^2 value. No volumetric electromagnetic simulation is needed. Following the CENELEC in-situ protocol [12, 13], we also form a body-representing vertical average from incident power-density samples at 1.1, 1.5, and 1.7 m above the floor.

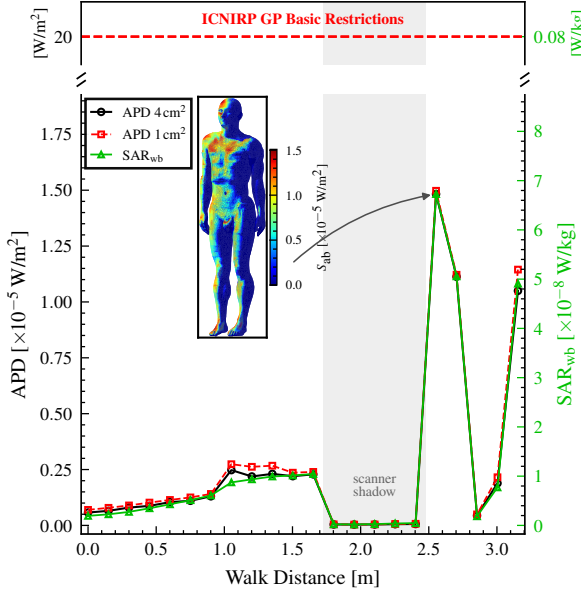


Figure 6.6: Exposure along the 3.2 m walk from the calibrated digital twin. $APD_{4\text{ cm}^2}$ and $APD_{1\text{ cm}^2}$ (left axis) and SAR_{wb} (right axis) versus walk distance. ICNIRP 2020 general-public basic restrictions are shown as dashed lines above the axis break. Inset: surface S_{ab} distribution on the phantom at the peak-exposure position.

Fig. 6.6 shows SAR_{wb} and $APD_{4\text{ cm}^2}$ along a 3.2 m walk through the room (Fig. 6.4c). The path goes from the far end of the stairwell, past the scan volume, to within 0.47 m of the antenna. At each of 22 positions, the ray tracer exports the per-path Jones vectors on the six Huygens-box planes. The wavelet sum (6.1) transfers the field to the body surface, and the pointwise surface law computes the exposure on a posed Duke phantom at each position. The total computation takes 31 s for the 22-position walk.

The peak $APD_{4\text{ cm}^2}$ is $1.5 \times 10^{-5} \text{ W/m}^2$ and the peak SAR_{wb} is $6.7 \times 10^{-8} \text{ W/kg}$, both more than 60 dB below the ICNIRP 2020 general-public basic restrictions (20 W/m^2 and 0.08 W/kg , respectively). The peak $APD_{1\text{ cm}^2}$ is $1.5 \times 10^{-5} \text{ W/m}^2$, nearly equal to the 4 cm^2 value (ratio 1.01). This ratio shows that the incident field is smooth at centimetre scale on the body surface, consistent with the scan-plane correlation result in Fig. 6.5b. The CENELEC three-height body average peaks at $4.2 \times 10^{-4} \text{ W/m}^2$, which is 44 dB below the 10 W/m^2 whole-body incident-power-density reference level. Exposure is maximized near the antenna, where direct and reflected paths add. Both quantities drop by two to three orders of magnitude in the scanner shadow, where the direct path is blocked.

This is a milliwatt-class source, so these margins are large and scale linearly

Table 6.3: Summary of validation results.

	Free-space (26 GHz)	Indoor (28 GHz)
Environment	Anechoic room	Stairwell
Tx elements	16 (D-MIMO)	4 (single set)
Scan area	50×50 cm	85×40×70 cm
Scan time	50 h	31 h
Comparison	NMAE, 1D slice	Blind held-out planes
Accuracy	17% NMAE (0.65 dB)	Beat corr. +0.55 to +0.79
Main limitation	Probe scattering	Stair-railing grating

with radiated power. A 1 W source at the same distance would still remain more than 20 dB below the basic restriction.

6.3.4.1 Parameter sensitivity

The held-out-plane smoothed-field scores (mean +0.49 across all four rotations) bound the local-power accuracy: the model under-predicts by a median of 1.9 dB (−0.8 to +4.9 dB, 5th–95th percentile on the $y=40$ cm held-out plane). We recompute the exposure walk with each of the four best candidates (one per held-out-plane rotation). The peak $\text{APD}_{4\text{ cm}^2}$ spans 7 dB across candidates, from 1.5×10^{-5} to 7.6×10^{-5} W/m². Even the worst-case candidate is 54 dB below the general-public basic restriction. Both the local-power error (≤ 5 dB) and the parameter spread (~ 7 dB) are small compared to this 54 dB margin to the basic restriction.

6.4 Validation summary

Table 6.3 collects the quantitative outcomes of both validation experiments.

The free-space NMAE is 17% on the horizontal slice, which shows that the hybridization procedure reproduces the beamformed hot-spot structure within the measurement uncertainty. The largest difference is scattering from the probe itself. The simulation omits scattering from the measuring probe, so this difference is expected. The broad field distribution, side lobes, central peak, and interference lines are reproduced qualitatively. Probe scattering causes the remaining asymmetry.

The indoor experiment has more free parameters: the geometry, material properties, antenna placement, and scan-frame alignment are all free parameters, and only phaseless magnitude data is available for comparison. Despite these degrees of freedom, the blind leave-one-plane-out validation produces beat-spectrum correlations of +0.55 to +0.79 on every held-out plane. The correlation grows monotonically with spatial averaging scale (Fig. 6.5b), which means that the model is more accurate for the spatially averaged quantities on which exposure limits are defined. The

largest model error comes from a metal grating (the stair railing) whose periodic diffraction falls outside the specular ray tracer.

The exposure values computed from the calibrated digital twin are >54 dB below the ICNIRP 2020 general-public basic restriction across all four candidate models. The 7 dB spread across candidates is small compared to this margin. These numbers represent a single antenna radiating milliwatts. Scaling to a higher transmit power or multiple base stations would reduce the margin proportionally, but would not change the validation methodology.

Both experiments use a single transmitter orientation and frequency. The pipeline has been validated at 26 and 28 GHz [FR2]. Validation at FR3 and sub-THz frequencies is future work. The indoor experiment uses a room of moderate complexity. A larger or more cluttered environment would add scattering from furniture, people, and partitions that the specular model would miss.

The city-scale application in the remainder of this chapter uses the same pipeline with outdoor urban environments and photogrammetric 3D building models.

6.5 From validation to city scale

The measurements in the preceding sections show that a physically parameterized ray-tracing model can reproduce the interference pattern measured in a real room and that the resulting exposure levels are tens of decibels below the basic restrictions. However, the validation covers one room and one transmitter. Earlier outdoor work extended the same route-to-body link to one outdoor path [14]. Moving from that path to ten cities creates a source-count problem. A ten-city study must represent many possible transmitter positions, but the cost of a forward ray trace grows with the source count. To make this step, the remainder of this chapter combines AI-assisted surface assignment with SAM 3 Agent, an adjoint ray tracer whose cost is independent of the source count, and the surface exposure law from Chapter 5. The goal is to compute route-level whole-body exposure in ten cities at 15 GHz [FR3].

6.6 AI-assisted surface assignment

This part is adapted from the ten-city study [15].

Geometry alone leaves one input missing. A photogrammetric city mesh [16, 17] provides the buildings, but its triangles have no material information. Street-level images supply that information. For each route, we align 360-degree panoramas from Mapillary [18] with a city mesh cropped to a 250 m radius around the route. Two fixed image-analysis models then run in sequence. First, Mask2Former assigns a Mapillary Vistas object class to every image pixel [19, 20]. Next, SAM 3 Agent assigns material and vegetation labels inside compatible object regions [21]. The model uses a fixed catalogue of 60 text prompts, including “brick facade”, “glass window” and “tree canopy”. Object labels select the prompts for each view.

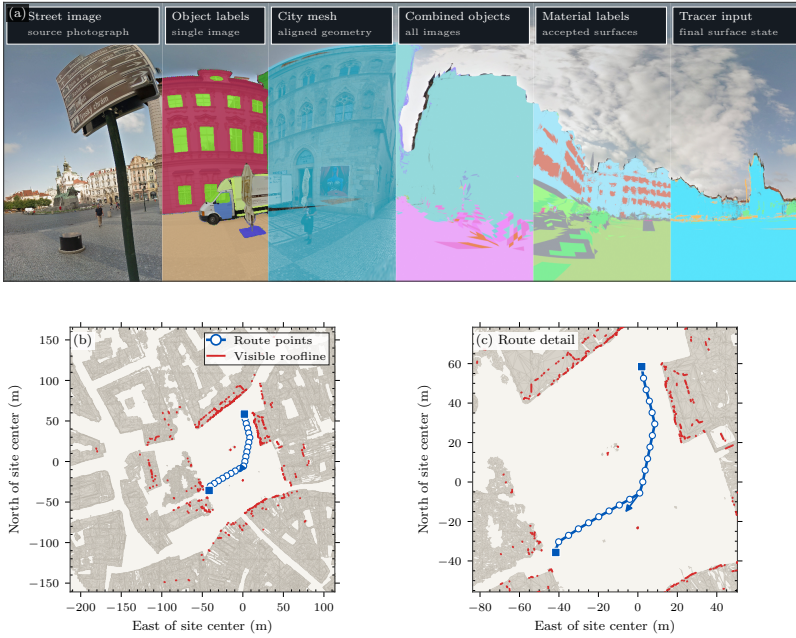


Figure 6.7: Study configuration at Prague Old Town Square. (a) A 360-degree street image is segmented and projected onto the city mesh to assign surface materials for ray tracing. (b) The 22 observation points and the visible roofline on a plan view. (c) Close-up of the route. The arrow shows the body model's direction of travel.

Instance scores must exceed 0.35, and the object and material labels must be compatible. The calculation projects both sets of labels onto visible mesh triangles using the known camera position and viewing direction.

Where multiple images cover the same triangle, the calculation combines their labels into one surface description, averaging observations within each camera and surface texel and combining cameras with confidence weights. Each assigned triangle has a link to its source image. Compatible structural labels replace the geometry-based material when their total normalized weight exceeds 0.5. Accepted weights are normalized and used to mix reflected powers. All other triangles keep the geometry-based default. The surface geometry remains fixed.

Fig. 6.7 shows how these inputs come together at Prague Old Town Square. A 360-degree street image is segmented and projected onto the city mesh to assign the surface materials used for RT. The plan view then places the 22 observation points and the visible roofline segments on the same mesh.

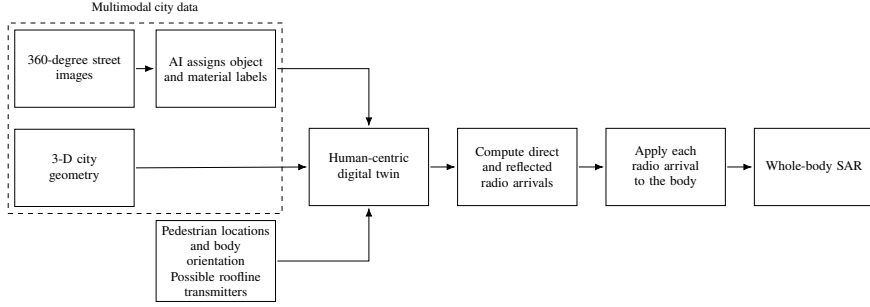


Figure 6.8: Flowchart of the method. Street images and city geometry give an AI-assisted digital twin. The route and possible transmitters give directional arrivals. The body model converts them to whole-body SAR.

6.7 Roofline transmitter model and adjoint ray tracing

The surface description now feeds the exposure calculation. Fig. 6.8 connects the surface-assignment stage to the route-level result. The image and geometry branches first form the human-centric digital twin. Route locations, body orientations, and possible roofline transmitters complete its inputs. The central path then computes directional arrivals and applies them to the body.

The source model and adjoint ray tracer define the two central stages. Together, they make the ray calculation independent of the number of sources.

6.7.1 Source model

The possible roofline transmitters in Fig. 6.8 represent a future distributed massive MIMO (DMaMIMO) architecture only to define possible access-point locations [14, 22]. Therefore, the model uses visible rooflines as possible transmitter locations. The calculation treats the possible sites as independent power sources and distributes expected transmitters uniformly per unit physical length of the roofline visible from the route. Their distribution in proportion to roofline length avoids tying the result to one deployment.

Let ρ_A be the expected active-site areal density and A_{crop} the crop area. For a roofline segment with endpoints $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$, ℓ_i is its physical three-dimensional length. The expected number of transmitters and the fraction assigned to segment i are

$$N_{\text{site}} = \rho_A A_{\text{crop}}, \quad p_i = \frac{\ell_i}{\sum_j \ell_j}, \quad \ell_i = \|\mathbf{p}_{i+1} - \mathbf{p}_i\|_2. \quad (6.3)$$

Thus, N_{site} sets the number of transmitters and p_i assigns a fraction of that number to segment i . Dividing by the total roofline length ensures that splitting one segment

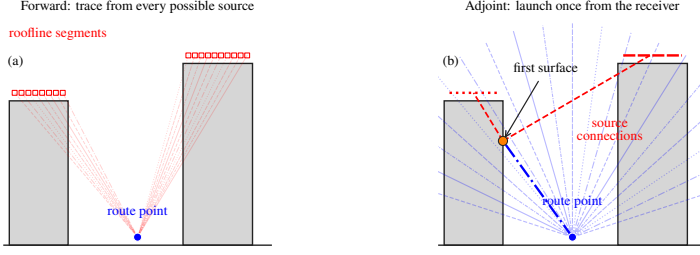


Figure 6.9: Forward and adjoint sampling for the first-diffuse term. (a) Forward sampling launches rays from every roofline segment toward the observation point, with cost scaling with the number of sources. (b) Adjoint sampling launches rays from the observation point. At the first blocking surface, next-event estimation uses a visibility ray toward a sampled roofline segment. The sampling budget is fixed per observation point.

into smaller numerical pieces does not add transmitters. The model uses three-dimensional length rather than horizontal projected length.

An unobstructed reference separates the source density from the scene geometry by summing the inverse-square contribution of every roofline segment:

$$D_{\text{ref}}(\mathbf{x}) = \sum_i \frac{p_i}{r_i(\mathbf{x})^2}, \quad S_{\text{ref}}(\mathbf{x}) = \frac{A_{\text{crop}} D_{\text{ref}}(\mathbf{x})}{4\pi}. \quad (6.4)$$

No visibility test enters D_{ref} . All reported quantities are normalized per unit $\rho_A P_{\text{EIRP}}$. Multiplication by $\rho_A P_{\text{EIRP}}$ recovers physical units, but only for a deployment that follows the same roofline transmitter model. The calculation omits transmitters and interactions outside the crop.

6.7.2 Adjoint ray tracing

With the source normalization fixed, the radio-arrival stage in Fig. 6.8 computes propagation to each route point. Standard forward RT launches rays from every source toward the receiver. Its computational cost grows with the source count. *Adjoint ray tracing* instead launches rays once from the receiver and follows them to the first blocking surface [23, 24]. At that surface, next-event estimation [25] samples a roofline segment according to its source weight and computes the connection’s visibility. The ray calculation is then independent of the number of sources. Fig. 6.9 shows the difference between forward and adjoint sampling.

The propagation result at each observation point has direct paths, one specular reflection, and one diffuse reflection. Let $\mathcal{D}$ contain the visible direct paths and $\mathcal{S}_1$ contain the accepted one-reflection specular paths. Their normalized powers are $\alpha_a = m_a^{(d)} / D_{\text{ref}}$ and $\beta_b = m_b^{(s)} / D_{\text{ref}}$. The diffuse estimate uses normalized angular-cell powers $\hat{\gamma}_q = \hat{m}_q^{(f)} / D_{\text{ref}}$. With $\delta_{\hat{\mathbf{k}}}$ denoting a unit point mass in

physical arrival direction $\hat{\mathbf{k}}$, the directional distribution is

$$\mu_{\mathbf{x}} = \sum_{a \in \mathcal{D}} \alpha_a \delta_{\hat{\mathbf{k}}_a^{(d)}} + \sum_{b \in \mathcal{S}_1} \beta_b \delta_{\hat{\mathbf{k}}_b^{(s)}} + \sum_{q=1}^Q \hat{\gamma}_q \delta_{\hat{\mathbf{k}}_q^{(f)}}. \quad (6.5)$$

The calculation uses $Q = 4096$ angular cells. The first two sums retain the exact directions and powers of the direct and specular paths. Only diffuse power is accumulated in the angular cells by Monte Carlo sampling. Each run launches 200,000 independent primary rays per route point, and only the diffuse estimate varies between runs.

The material model combines unpolarized Fresnel power with a Rayleigh roughness term for the specular component. The remaining power enters a Lambertian diffuse term, and the components add incoherently.

For a surface patch receiving power P_{hit} , the Lambertian term has angular power density [26]

$$\frac{dP_{\text{diff}}}{d\Omega} = \frac{\rho_{\text{diff}} P_{\text{hit}}}{\pi} [\hat{\mathbf{n}} \cdot \hat{\boldsymbol{\omega}}]_+. \quad (6.6)$$

Here, $\hat{\mathbf{n}}$ is the outward surface normal, $\hat{\boldsymbol{\omega}}$ is the outgoing direction, and $[x]_+ = \max(x, 0)$. The fraction ρ_{diff} includes the Fresnel reflection and the roughness-dependent share assigned to diffuse power. The factor $1/\pi$ normalizes the cosine lobe, so integration over the outward hemisphere gives $\rho_{\text{diff}} P_{\text{hit}}$. The sampled path ends after this first diffuse reflection. The calculation omits further specular reflections and all higher-order interactions. Woody vegetation identified in the images is transparent to rays because the city mesh has no canopy volume. Material parameters follow ITU-R P.2040 [8].

6.8 Directional body coupling

The final two blocks in Fig. 6.8 pass the arrival directions in Eq. (6.5) to the body. For outward body-surface normal $\hat{\mathbf{n}}(\mathbf{r})$, define the cosine projection $g(\mathbf{r}, \hat{\mathbf{k}}) = [\hat{\mathbf{n}}(\mathbf{r}) \cdot (-\hat{\mathbf{k}})]_+$. The function g sets the absorbed fraction to zero where the surface faces away from the incoming direction. The normalized absorbed power density is

$$\tilde{S}_{\text{ab}}(\mathbf{r}, \mathbf{x}) \equiv \frac{S_{\text{ab}}(\mathbf{r}, \mathbf{x})}{\rho_A P_{\text{EIRP}}} = T_0 S_{\text{ref}}(\mathbf{x}) \int_{\mathbb{S}^2} g(\mathbf{r}, \hat{\mathbf{k}}) d\mu_{\mathbf{x}}(\hat{\mathbf{k}}). \quad (6.7)$$

The angular integral sums the direct, specular, and diffuse arrivals while retaining their incoming directions. Here, T_0 is the normal-incidence power-transmission coefficient from the IT'IS tissue database at 15 GHz [FR3] [27]. This coefficient approximates the absorption cross section for incoherent, unpolarized illumination. The calculation applies this directional absorption to the 56,024-element Duke anatomical mesh [10].

The body coupling in Eq. (6.7) is the incoherent form of the surface exposure law derived in Chapter 5. Because the roofline sources are independent and numerous,

phases between paths are random, so powers add directly and the coherent operator reduces to this incoherent sum. The constant T_0 is the pseudo-Brewster normal-incidence transmission coefficient, the same approximation used in Chapter 5 for unpolarized illumination.

For the triangle area A_r at position $\mathbf{r}$ and body mass m_{body} , the normalized whole-body quantities are

$$\begin{aligned}\tilde{P}_{\text{abs}}(\mathbf{x}) &\equiv \frac{P_{\text{abs}}(\mathbf{x})}{\rho_A P_{\text{EIRP}}} = \sum_{\mathbf{r}} A_r \tilde{S}_{\text{ab}}(\mathbf{r}, \mathbf{x}), \\ \widetilde{\text{SAR}}_{\text{wb}}(\mathbf{x}) &\equiv \frac{\text{SAR}_{\text{wb}}(\mathbf{x})}{\rho_A P_{\text{EIRP}}} = \frac{\tilde{P}_{\text{abs}}(\mathbf{x})}{m_{\text{body}}}.\end{aligned}\tag{6.8}$$

$\tilde{P}_{\text{abs}}$ has units m^2 , and $\widetilde{\text{SAR}}_{\text{wb}}$ has units $\text{m}^2 \text{ kg}^{-1}$. A physical whole-body SAR value requires multiplication by the deployment's $\rho_A P_{\text{EIRP}}$. Therefore, the normalized results apply to the stated source model rather than a specific deployed network. The body model faces along the direction of travel at each route point, so a different route would change both position and orientation.

6.9 Validation and convergence

Before interpreting the ten-city results, we compare the stored total with the sum of the direct, specular and diffuse components. We then compare the diffuse estimate with two reference calculations and examine convergence across random seeds.

6.9.1 Component closure

The direct, exact order-1 specular, and first-diffuse fields sum to the stored total with a maximum absolute residual of $1.214 \times 10^{-17} \text{ m}^{-2}$ across all 10,432 body fields (163 points $\times$ 64 runs). The GPU body-coupling result matches the double-precision CPU reference to a maximum relative difference of 6.64×10^{-16} . These checks verify the input files, the addition of components, and the CPU-to-GPU agreement.

6.9.2 Controlled scene

The component checks establish arithmetic closure, but they do not test the random diffuse estimate. Therefore, the controlled comparison in Fig. 6.10 tests this stochastic component in a simplified scene. The open-square scene has 27 sources, six receivers, eight triangles, and one diffuse reflection, with no specular reflection, refraction, or diffraction.

Deterministic surface quadrature uses 2,097,152 samples. The adjoint estimate uses 50,000 primary rays for each of four seeds. An independent Sionna RT forward calculation [28] uses 50,000 samples per source for each of three seeds. Validation gives a maximum difference of 1.43% between the adjoint estimate and quadrature

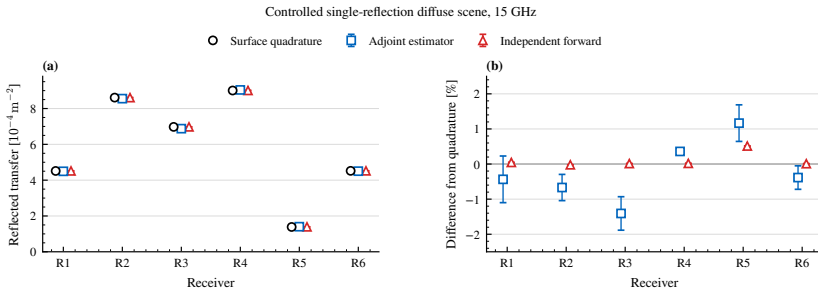


Figure 6.10: Controlled validation of the first-diffuse transfer. (a) Deterministic surface quadrature, the adjoint estimate, and the independent Sionna RT forward calculation at six receivers. (b) Signed percentage difference from quadrature. Error bars give the standard error across four adjoint seeds and three Sionna seeds.

for the reflected component. A separate comparison of total received power gives a maximum adjoint-to-Sionna difference of 0.80%. The comparison checks diffuse normalization, visibility, inverse-square loss, and cosine terms in this one-reflection scene. Therefore, the comparison isolates the diffuse calculation.

6.9.3 Convergence across runs

Between 48 and 64 runs, the largest pointwise change in total received power is 0.32% at a shadowed point in Mexico City. The next largest change is 0.13% in Tokyo Hachiko. The maximum is below 0.023% on each of the other eight routes, and every route-median whole-body SAR is stable.

In Mexico City, the largest single-run diffuse estimate at one shadowed point is 5,738 times the median run estimate. This concentration produces the large lower-tail changes seen in Table 6.5. This concentration is specific to the fixed routes and quantifies random ray-sampling convergence.

With the component calculation verified, Fig. 6.11 shows convergence across the selected run counts for five routes. Route medians stabilize within a few runs. The shadowed points in Mexico City and Tokyo converge slowest, because their first-diffuse estimates depend on rare strong hits.

6.10 City-scale exposure assessment

The method is applied to ten street-level routes across three continents.

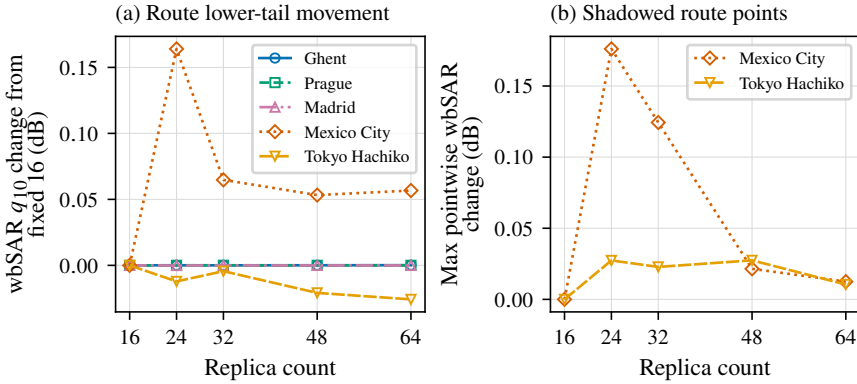


Figure 6.11: Convergence of normalized whole-body SAR. (a) Change in the route’s 10th percentile relative to the fixed 16-run estimate for five routes. (b) Maximum absolute change between successive run counts at the shadowed points in Mexico City and Tokyo Hachiko. The estimates at these points depend on weak or rare diffuse contributions.

6.10.1 Routes and computation

With convergence established, Table 6.4 summarizes the ten cities and their fixed routes. Each route follows a connected street corridor covered by aligned 360-degree street images. The calculation places fixed observation points along that corridor, including interpolated positions between image locations, so the number of images and the number of observation points can differ. The 163 route points are fixed case-study observations that describe the selected routes. The body model faces along the direction of travel, so a different route would change both position and orientation.

Every site uses 15 GHz and a photogrammetric city mesh cropped to a 250 m radius ($A_{\text{crop}} = \pi R_{\text{crop}}^2 = 196,349.54 \text{ m}^2$). The Duke body model has 56,024 surface elements and a mass of 72.4 kg. Each point has 64 independent runs with seeds 7 through 70. Each run uses 200,000 primary rays and 4,096 fixed angular cells for the diffuse term. The resulting 10,432 body fields contain 2.086 billion primary rays. Ray calculation takes 5.95 to 73.77 s per city on one A6000 GPU. These times exclude image acquisition, alignment, depth estimation, and surface-label assignment because their full times were not recorded.

6.10.2 Route exposure distributions

After these checks, Fig. 6.12 compares the fixed-route empirical distributions and route-mean component shares. Table 6.5 complements the figure with exact quantiles, finite multipath surplus, shadowed-point counts, and convergence. Normalized whole-body SAR is reported in $\text{m}^2 \text{ kg}^{-1}$ per unit $\rho_A P_{\text{EIRP}}$. A physical whole-body SAR value requires multiplication by the deployment’s areal source density and

Table 6.4: Ten fixed routes with observation-point counts, route spans, and computation times.

City	Route points	Route span (m)	Wall time (s)
Brussels	14	87.00	32.16
Ghent	10	49.04	6.59
Krakow	16	116.10	31.76
London	22	121.10	73.77
Madrid	14	73.47	8.06
Mexico City	11	60.79	5.95
Milan	23	128.43	69.02
Prague	22	119.39	39.00
Tokyo Hachiko	16	87.38	10.02
Toulouse	15	82.47	37.87
Total	163	925.17	314.20

EIRP.

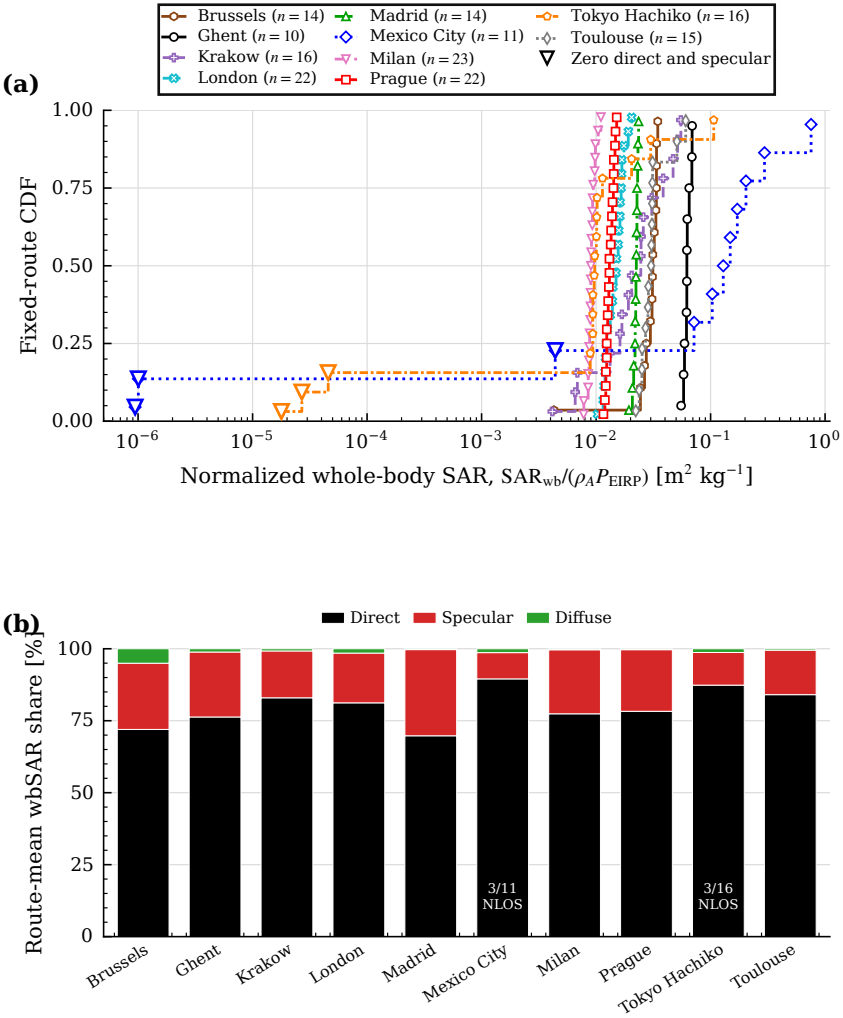


Figure 6.12: Normalized whole-body SAR on the ten fixed routes. (a) Empirical CDFs include all 163 route points. Hollow triangles mark the six points with zero direct and zero order-1 specular transfer. (b) Route-mean component shares of whole-body SAR. The distributions describe the selected routes under the stated source model.

The largest route median (Mexico City, $0.1291 \text{ m}^2 \text{ kg}^{-1}$) is 14.31 times the smallest (Milan, $0.009016 \text{ m}^2 \text{ kg}^{-1}$). Mexico City and Tokyo Hachiko have the widest spread along a route and the lowest tails.

Table 6.5: Fixed-route exposure summary. Whole-body SAR quantiles are normalized per unit $\rho_A P_{\text{EIRP}}$ and have units $\text{m}^2 \text{ kg}^{-1}$. Surplus is computed only at points with nonzero direct power. The last column is the maximum pointwise total-power change from 48 to 64 runs.

City	Normalized whole-body SAR [$\text{m}^2 \text{ kg}^{-1}$]			Median surplus (dB)	Zero direct and order-1 specular	Max total-power change [%]
	q_{10}	q_{50}	q_{90}			
Brussels	0.025022	0.031187	0.033714	1.431	0	0.00702
Ghent	0.057835	0.062047	0.068668	1.155	0	0.00257
Krakow	0.006717	0.022520	0.049268	0.917	0	0.00673
London	0.011746	0.015008	0.017444	0.901	0	0.01953
Madrid	0.020913	0.022381	0.023170	1.552	0	0.00234
Mexico City	1.01×10^{-6}	0.129061	0.295766	0.686	3	0.32014
Milan	0.008529	0.009016	0.009861	1.136	0	0.00424
Prague	0.012157	0.013074	0.014595	1.091	0	0.00282
Tokyo Hachiko	3.63×10^{-5}	0.009674	0.025200	0.839	3	0.12868
Toulouse	0.024312	0.030217	0.042915	0.835	0	0.00150

Of the 157 points with line of sight, direct power is the largest contribution at 156. At Brussels standpoint 2, single-reflection specular power is the largest component. Mexico City points 0, 1, and 3 and Tokyo Hachiko points 13, 14, and 15 have zero direct and zero single-reflection specular power. Single-reflection diffuse power is the only nonzero contribution at these six points. A propagation model that omits the diffuse term would assign zero exposure there.

Across all 163 points, the separate component medians are 78% direct, 20% specular, and 0.5% diffuse. They do not sum to 100% because each component has a separate median over the 163 route points. The small diffuse median does not describe the six fully shadowed points.

The route-mean shares in Fig. 6.12(b) show that direct power is the largest route-mean component at all ten routes and that the diffuse share increases at the routes with shadowed points.

6.10.3 Material sensitivity

These route results use image-derived materials. Therefore, a paired control for Madrid and Mexico City replaces all image-derived materials with the default geometry-based materials while keeping the mesh, route, roofline model, body, seeds, sampling budget, and propagation steps identical. Each reported change is $10 \log_{10}(x_{\text{image}}/x_{\text{geometry}})$.

At Madrid, the image-derived case increases normalized whole-body SAR by 5.5%, 5.9%, and 6.4% at q_{10} , q_{50} , and q_{90} . At Mexico City, it gives a roughly 305-fold larger q_{10} , a 3.6% smaller median, and a 2.4% larger q_{90} . The large q_{10} ratio comes from the three fully shadowed points, where both totals are near zero

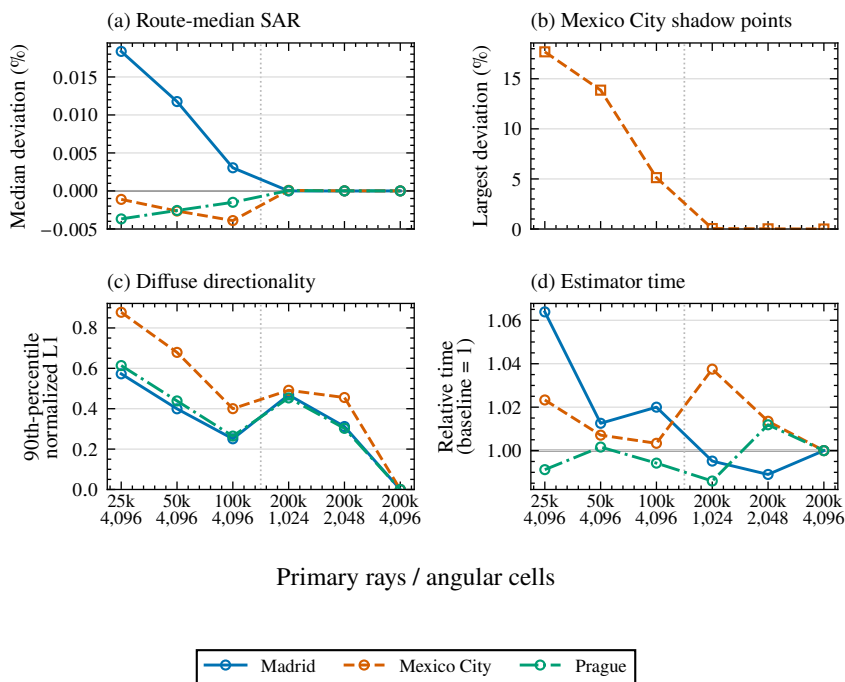


Figure 6.13: Sensitivity to the ray budget and angular cell count. Route-median SAR deviation, the largest shadow-point deviation in Mexico City, diffuse directionality, and timing stabilize at the baseline of 200,000 rays and 4,096 angular cells.

and diffuse power is the only nonzero contribution. Direct power is identical in every pair.

At Madrid, the image-derived materials increase the route-median specular component by 54% and reduce the diffuse component by 94%, but increase the total median by only 5.9%. This paired control tests the surface parameters and the treatment of woody vegetation as nonblocking. Independent surface measurements are required for a material-accuracy assessment.

6.10.4 Ray budget and angular resolution

Finally, Fig. 6.13 shows the sensitivity of the computation to the ray budget and angular cell count. Four diagnostics are tracked: route-median whole-body SAR, maximum pointwise change, diffuse directional convergence, and timing. At the baseline of 200,000 rays and 4,096 angular cells, all four diagnostics have converged. The estimates at Mexico City’s shadowed points stabilize slowest, consistent with the run convergence analysis above.

6.10.5 Discussion

Route-median normalized whole-body SAR differs by a factor of 14.31 across the ten routes. Fig. 6.8 links this spread to street width, building height, roofline visibility, surface materials, canopy, and directional body coupling. Each empirical distribution describes its fixed route and its observation points.

Under this source model, a common multiplicative change in active-site density or EIRP rescales every route's whole-body SAR equally, so it cancels from the ratio of route medians. Route-specific changes in transmitter placement, geometry or material assignment can change that ratio.

The single-reflection diffuse component is small at most points (0.5% overall median), but it is the only nonzero contribution at the six fully shadowed points. Its small share where line of sight exists does not make it dispensable where buildings block all direct and specular paths. A propagation model that omits the diffuse term would assign zero exposure to those six positions. This is consistent with the surface exposure law of Chapter 5: the incoherent law scales linearly with the incident power density from each direction, so body-coupling accuracy depends on the propagation calculation.

The paired material control tests the effect of image-derived materials on the body results. The direct term is identical in both cases, so all observed changes come from the materials used by the reflected and diffuse terms. In Madrid, the specular and diffuse component changes have opposite signs, yet the route-median normalized whole-body SAR increases by only 5.9%. The Mexico City route median decreases by 3.6%. Its much larger lower-tail ratio comes from the three fully shadowed route points where both estimates are close to zero. The paired cases differ in their assigned materials and in their treatment of woody canopy. The image-derived case treats identified canopy as transparent because the city mesh has no canopy volume. Therefore, the comparison measures sensitivity to both the material assignment and the vegetation rule together. Independent surface measurements are required for a material-accuracy assessment.

This city-scale study covers ten selected routes at one frequency with one body model, one roofline source model, and one set of image-derived surface labels. A physical scaling applies when the transmitter distribution matches this source model. The propagation calculation includes direct paths and one specular or diffuse reflection. The controlled comparison covers the diffuse estimate in a one-reflection scene.

Variation across 64 runs quantifies random ray-sampling error. Image alignment, geometry, material labels, route choice, transmitter placement, body shape, and body orientation form separate sources of uncertainty. Ray calculation time ranges from 5.95 to 73.77 s per site on one A6000 GPU. The recorded times cover the ray and body calculations.

The adjoint formulation developed here extends the hybrid RT/FDTD pipeline of Chapters 3 and 4 to a multi-city application. The propagation step scales independently of the source count, and the body coupling step reuses the same Fresnel-based surface exposure law derived in Chapter 5.

6.11 Discussion and conclusion

This chapter spans three spatial scales: a single hot-spot in an anechoic room, a multipath field in a stairwell, and pedestrian routes across ten cities. At each scale, the exposure models from the preceding chapters are validated or applied.

In the anechoic room, the hybrid ray-tracing/FDTD pipeline from Chapter 3 reproduces the measured beamforming hot-spot with 17% normalized mean absolute error. The five hot-spot features (large-scale envelope, wavelength-sized sidelobes, constructive interference peak, standing-wave fringes, and probe-scattering asymmetry) appear in the measurement. The first four also appear in the simulation. Probe-scattering asymmetry does not. This controlled comparison validates the hybridization step that couples ray-traced multipath to near-field exposure computation.

In the stairwell, the digital twin calibrated from phaseless 28 GHz scans predicts the held-out interference pattern with beat-spectrum Pearson correlation $+0.55$ to $+0.79$. The agreement grows with the spatial averaging scale, so the model predicts the spatially averaged quantities on which exposure limits are defined. The largest model error comes from a periodic metal grating (the stair railing) that specular ray tracing cannot represent. The resulting exposure is over 54 dB below the ICNIRP 2020 general-public basic restrictions [11] for all four held-out configurations, with a 7 dB spread across candidates. Both the local-power error and the parameter spread are small compared to this margin.

At city scale, the adjoint ray tracer and SAM 3 Agent surface assignment give route-level whole-body SAR at 163 observation points across ten cities. Route-median SAR differs by a factor of 14.31 across the ten routes. Street width, building height, roofline visibility, and surface materials all differ between the selected routes. Therefore, the 14.31-fold contrast describes these routes under this model. Direct power is the largest component at 156 of the 157 points with line of sight. Single-reflection specular power is largest at the remaining point in Brussels. The diffuse component is the only nonzero contribution at six fully shadowed points. A propagation model without diffuse power would assign zero exposure there. Relative to geometry-based defaults, the image-derived materials increase the Madrid route median by 5.9% and decrease the Mexico City route median by 3.6%. The lower-tail ratio in Mexico City is large because both estimates are near zero at three shadowed points.

The three parts of this chapter use both interface objects and both body solvers. In the anechoic room, the Huygens box couples the ray-traced field to FDTD on an anatomical phantom. In the stairwell, a Huygens box around the phantom couples the calibrated twin's field to the pointwise surface law of Chapter 5. At city scale, far-field paths are the input to the same surface law. The far-field assumption is valid outdoors because the base-station distance is large compared to the body size.

In this chapter, we validated the hybrid ray-tracing exposure pipeline against measurements and applied it to compute route-level exposure across ten cities.

In a controlled anechoic environment at 26 GHz, the hybridization of ray-

traced multipath onto a Huygens box reproduced the measured beamforming hot-spot with 17% normalized mean absolute error. In a realistic indoor stairwell at 28 GHz, a digital twin calibrated from phaseless robotic scans predicted the held-out interference beat spectrum with Pearson correlation +0.55 to +0.79. A Huygens box around the phantom coupled the twin's field to the pointwise surface law of Chapter 5, and the computed exposure was over 54 dB below the ICNIRP 2020 general-public basic restrictions.

At city scale, an adjoint ray tracer whose cost is independent of the number of sources computed route-level whole-body SAR at 163 observation points across ten cities at 15 GHz. Route-median SAR differed by a factor of 14.31 across routes. Direct power was the largest component at 156 of the 157 points with line of sight. Single-reflection specular power was largest at the remaining point in Brussels. At six fully shadowed points, diffuse power was the only nonzero contribution. Validation gave maximum differences of 1.43% from deterministic quadrature and 0.80% from Sionna RT. Increasing the number of runs from 48 to 64 changed the total at any point by at most 0.32%. The ten-route calculation took 314 s on a single GPU.

The indoor specular ray model is least accurate near fine periodic structures such as the stair railing grating. At city scale, the propagation calculation includes direct paths and one diffuse event at one frequency, with one body model and one source distribution. The controlled diffuse validation covers the stochastic estimate in a one-reflection scene.

In the next chapter, we compare the methods developed throughout the thesis and state the conclusions.

6.A Holographic phase retrieval

This appendix describes a phase retrieval method that reconstructs the full vector electromagnetic field from phaseless electric-field measurements. The method is based on the Gerchberg–Saxton (GS) algorithm [29, 30] and uses a cluster-based representation of the scattering environment derived from Green's tensor. In a synthetic test case the algorithm converged to below 1% error. On the 28 GHz indoor measurements from Section 6.3, it did not converge. Three causes are discussed below.

6.A.1 Method

6.A.1.1 Cluster-based field representation

We start from the integral representation of the electric field in terms of the free-space Green's tensor [31]:

$$\mathbf{e}(\mathbf{r}) = -j\omega\mu_0 \int_S \overline{\overline{\mathbf{G}}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{j}(\mathbf{r}') d\mathbf{r}', \quad (6.9)$$

where $\mathbf{j}$ is the equivalent current density on the surfaces S of the environment and

$$\overline{\overline{\mathbf{G}}}(\mathbf{r}, \mathbf{r}') = \left(\mathbf{I} + \frac{1}{k^2} \nabla \nabla \right) G(R), \quad G(R) = -\frac{\exp(jkR)}{R}, \quad (6.10)$$

with $R = \|\mathbf{r} - \mathbf{r}'\|$.

In the far-field limit ($kR \rightarrow \infty$), the non-radiative components become negligible and the tensor reduces to

$$\overline{\overline{\mathbf{G}}}(\mathbf{r}, \mathbf{r}') \xrightarrow{kR \rightarrow \infty} \frac{\exp(-jk|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|} (\mathbf{I} - \hat{\mathbf{R}}\hat{\mathbf{R}}), \quad (6.11)$$

where $\hat{\mathbf{R}} = (\mathbf{r} - \mathbf{r}')/|\mathbf{r} - \mathbf{r}'|$. The term $\mathbf{I} - \hat{\mathbf{R}}\hat{\mathbf{R}}$ projects the current density onto the plane perpendicular to $\hat{\mathbf{R}}$, so that (6.11) locally behaves as a plane wave.

We replace the continuous surface integral by a sum over C *scattering clusters*, each assumed to be in the far field of the observation point:

$$\mathbf{e}(\mathbf{r}) \approx \sum_{c=1}^C \left(a_c^\theta \hat{\mathbf{u}}_c^\theta(\mathbf{r}) + a_c^\phi \hat{\mathbf{u}}_c^\phi(\mathbf{r}) \right) \frac{\exp(-jk|\mathbf{r} - \mathbf{r}_c|)}{|\mathbf{r} - \mathbf{r}_c|}. \quad (6.12)$$

Here a_c^θ and a_c^ϕ are the complex coefficients of cluster c for the θ and ϕ polarizations, $\hat{\mathbf{u}}_c^{\theta/\phi}(\mathbf{r})$ are the corresponding spherical unit vectors, and $\mathbf{r}_c$ is the cluster location.

6.A.1.2 Linear system

We consider K measurement locations $\mathbf{r}_i$ where only the magnitude of the y -component of the electric field is recorded. Projecting (6.12) onto $\hat{\mathbf{u}}_y$ and collecting all K observations gives the linear system

$$\mathbf{y} = \mathbf{H} \mathbf{x}, \quad (6.13)$$

where $\mathbf{y} \in \mathbb{C}^K$ contains the y -components of the field at the measurement locations, $\mathbf{x} = [\mathbf{a}^\theta; \mathbf{a}^\phi]^\top$ collects all $2C$ cluster coefficients, and the channel matrix $\mathbf{H} \in \mathbb{C}^{K \times 2C}$ has elements

$$h_{ic}^{\theta/\phi} = \hat{\mathbf{u}}_y \cdot \hat{\mathbf{u}}_c^{\theta/\phi}(\mathbf{r}_i) \frac{\exp(-jk|\mathbf{r}_i - \mathbf{r}_c|)}{|\mathbf{r}_i - \mathbf{r}_c|}. \quad (6.14)$$

The system (6.13) is solved in the least-squares sense with the Moore–Penrose pseudoinverse [32, 33]:

$$\mathbf{x} = \mathbf{H}^+ \mathbf{y}, \quad \mathbf{H}^+ = \mathbf{V} \mathbf{\Sigma}^+ \mathbf{U}^H, \quad (6.15)$$

where $\mathbf{U} \mathbf{\Sigma} \mathbf{V}^H$ is the singular value decomposition of $\mathbf{H}$.

Input: Channel matrix $\mathbf{H}$, measured amplitudes $\mathbf{y}^{\text{meas}}$, convergence threshold $\varepsilon_{\text{conv}}$

Output: Cluster coefficients $\mathbf{x}^{(n)}$

```

 $n \leftarrow 0;$ 
 $\mathbf{x}^{(0)} \leftarrow \mathbf{H}^+ \mathbf{y}^{\text{meas}};$ 
 $\mathbf{y}_{\text{sim}}^{(0)} \leftarrow \mathbf{H} \mathbf{x}^{(0)};$ 
 $\varepsilon^{(0)} \leftarrow \|\mathbf{y}_{\text{sim}}^{(0)} - \mathbf{y}^{\text{meas}}\| / \|\mathbf{y}^{\text{meas}}\|;$ 
while  $\varepsilon^{(n)} \geq \varepsilon_{\text{conv}}$  do
  for  $i = 1, \dots, K$  do
     $y_i^{(n)} \leftarrow |y_i^{\text{meas}}| y_{i,\text{sim}}^{(n)} / |y_{i,\text{sim}}^{(n)}|;$  // impose measured
    amplitude
  end
   $\mathbf{x}^{(n+1)} \leftarrow \mathbf{H}^+ \mathbf{y}^{(n)};$  // inverse transform
   $n \leftarrow n + 1;$ 
   $\mathbf{y}_{\text{sim}}^{(n)} \leftarrow \mathbf{H} \mathbf{x}^{(n)};$  // forward transform
   $\varepsilon^{(n)} \leftarrow \|\mathbf{y}_{\text{sim}}^{(n)} - \mathbf{y}^{\text{meas}}\| / \|\mathbf{y}^{\text{meas}}\|;$ 
end

```

Algorithm 1: Holographic phase retrieval (Gerchberg–Saxton).

6.A.1.3 Gerchberg–Saxton iterative algorithm

Only the magnitudes $\mathbf{y}^{\text{meas}} = |\mathbf{y}|$ are known from the measurement. The forward transform $\mathbf{y} = \mathbf{H}\mathbf{x}$ and its pseudoinverse are the spatial equivalents of the Fourier transform pair between the *cluster domain* and the *field domain*. The GS algorithm iterates between these two domains, replacing the amplitudes with the measured values at each step. Algorithm 1 lists the procedure.

The output coefficients are substituted into (6.12) to give the full vector electric field $\mathbf{e}(\mathbf{r})$ at any point in the domain. The magnetic field follows from the curl of $\mathbf{e}$.

6.A.2 Synthetic validation

The method was tested in a synthetic scenario at 28 GHz. A cubic domain of 1 m^3 was centred on the origin with $K = 1000$ receivers placed randomly inside a cross-sectional slice at $z = 0$. Ten scattering clusters ($C = 10$) were placed at 1 m from the centre. A reference field was computed from these clusters with known coefficients. The cluster distances were then randomly perturbed by up to 1 cm and the coefficient vector was replaced by random complex numbers on the unit disk. Starting from the magnitude of the y -component of the perturbed field, Algorithm 1 recovered the original fields and cluster coefficients.

Fig. 6.14 shows the normalised error $\varepsilon^{(n)}$ as a function of iteration number. The algorithm reached the 1% convergence threshold in 23 iterations. The reconstructed field pattern is visually identical to the reference.

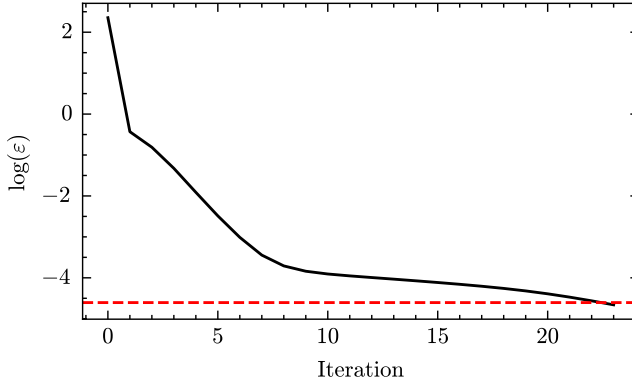


Figure 6.14: Normalised error $\varepsilon^{(n)}$ of the GS algorithm in the synthetic test case at 28 GHz. The dashed line marks the 1% convergence threshold. The algorithm converges in 23 iterations.

6.A.3 Indoor environment results

The same algorithm was applied to the 28 GHz stairwell measurements from Section 6.3. The channel matrix $\mathbf{H}$ was computed with a GPU-accelerated code. $K = 1000$ receiver locations were selected at random within the measured slices. Cluster locations were taken from the digital twin: all surfaces with line of sight to the evaluation domain were identified in Blender, and Poisson-disk sampling with Bridson's algorithm [34] placed clusters at a minimum spacing of 5 cm.

The algorithm did not converge. The mean amplitude deviation between measured and reconstructed fields across all five slices was 28%. Three causes are discussed below.

First, the cluster decomposition (6.12) assumes that every observation point lies in the far field of every cluster. Several scatterers in the stairwell, most prominently the metallic positioning robot, are within centimetres of some evaluation points. The Fraunhofer distance $2D^2/\lambda$ for a characteristic robot dimension $D = 4.5$ cm at 28 GHz is 37.8 cm, larger than many cluster-to-receiver distances in the measurement volume.

Second, at $\lambda = 10.7$ mm, the positions of all surfaces in the twin must be accurate to a few millimetres for the simulated phases to match the physical reality. The architectural model of the building was converted from Revit to OpenUSD and checked against distance measurements in the room, but residual alignment errors remain.

Third, the Narda 5G FR2 probe is calibrated in free space. In the stairwell, metallic objects near the probe tip alter the coupling and can shift the measured amplitude from the calibrated value.

The linear system is under-determined ($K \ll 2C$) and admits many solutions, so the algorithm tolerates moderate model errors, but the combination of the three

effects above is too large for convergence.

Section 6.3.2 uses a differentiable ray tracer to calibrate the digital twin directly from the measured amplitudes, without phase recovery. The amplitude data from the stairwell measurement is the ground truth for that calibration.

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7

Conclusions

“All models are wrong but some are useful.”

— George E. P. Box

Realistic electromagnetic exposure assessment requires connecting a wireless deployment to the absorbed dose in a human body across five orders of magnitude in spatial scale. Until now, no computational framework covers the range from the propagation environment (~ 100 m) to the absorbing tissue (sub-mm skin depth at millimeter-wave (mmWave) frequencies) at acceptable cost. This thesis developed a set of methods, balancing generality for speed, with two explicit interfaces between the environment and the body. This chapter answers the four research questions, compares the methods, states the main findings, and identifies limitations and directions for future work.

7.1 Research questions

RQ1: What is the full-wave dosimetric baseline across age, frequency, and exposure scenario, and which basic restriction (whole-body SAR, local SAR, or APD) binds first?

Chapter 2 established the baseline from 550 Finite-Difference Time-Domain (FDTD) simulations across four anatomical phantoms (two adults, two children), 15 frequencies from 450 MHz to 26 GHz, and both environmental and auto-induced exposure. The main finding is that reference-level compliance does not always

guarantee basic-restriction compliance. Children exceed the whole-body basic restriction near 2140 MHz (Thelonious: 145%, Eartha: 122%), whereas adult phantoms remain below 82% in every configuration. Under the simulated focused fields normalized to a summed incident component power density of 10 W/m^2 , all four phantoms exceed the localized basic restriction at 3500 MHz (131–158%). At 7 GHz, the child phantom reaches an APD of 103% of the basic restriction, within the $\pm 12\%$ modelling uncertainty. To the best of our knowledge, this is the first child–adult far-field APD comparison across 7–15 GHz. These results are limited to four phantoms in a standing posture, without time-averaging or traffic-weighted exposure.

RQ2: How can site-specific propagation be coupled to full-wave dosimetry at mmWave frequencies, and what does the coupling reveal about distributed versus collocated MaMIMO architectures?

Chapters 3 and 4 coupled ray-traced or stochastic-channel propagation to FDTD through a Huygens surface. The method extends to mmWave frequencies in both indoor (3.5 and 28 GHz) and outdoor (28 GHz) environments. The consistent finding is that distributed and cell-free massive Multiple-Input Multiple-Output (MaMIMO) architectures produce lower peak exposure than collocated deployments at equal total radiated power: a factor of 2–3 reduction indoors and a ~ 20 dB reduction in dynamic range outdoors. The mechanism is that many distributed access points limit the worst-case incident field at any single location. The highest computed exposure across all configurations is 4% of the ICNIRP limits (collocated, 3.5 GHz, 320 W). However, each body evaluation still requires a full FDTD simulation, and the cost scales as f^4 . This cost is the reason for the closed-form methods of Chapter 5.

RQ3: Can the absorbed power be expressed in closed form, accurately enough to replace full-wave dosimetry and fast enough for beamformer design and city-scale assessment?

Chapter 5 derived two closed-form expressions. The incoherent law factors the whole-body absorbed power into a flux-weighted Fresnel transmission $\bar{T}(f)$ times a body shape factor A_{ab}/A . The coherent operator expresses the absorbed power under a precoder $\mathbf{w}$ as a quadratic form $\mathbf{w}^H \mathbf{Q} \mathbf{w}$, assembled from the same ray-traced paths that determine the communication channel. Both formulations match FDTD within the 7% tissue-dielectric uncertainty. The cost per full-body map is below 10 ms on a GPU, compared to hours or weeks for FDTD at mmWave frequencies. Exposure-Constrained Beamforming (ECBF) follows from the coherent operator: at half the MRT signal power, ECBF reduces the median whole-body absorbed power by a factor of 5.29 (interquartile range 4.43–6.49) across 746 496 full-body maps. These results are limited to far-field illumination, a flat-interface model, and a single-user beamformer. The first limitation is partially addressed in Chapter 6, which couples the surface law to Huygens-box fields in an indoor environment where the far-field assumption on the illumination does not hold.

RQ4: Do the simulated fields agree with measurements in controlled and in realistic environments?

Chapter 6 investigated and applied the pipeline in two environments. In a controlled anechoic environment at 26 GHz, the hybrid Ray-Tracing (RT)/FDTD procedure reproduced the measured beamforming hot-spot with 17% normalised mean absolute error. In a realistic indoor stairwell at 28 GHz, a digital twin calibrated from phaseless robotic scans predicted the held-out interference pattern with beat-spectrum Pearson correlation $+0.55$ to $+0.79$. The computed exposure was over 54 dB below the ICNIRP 2020 general-public APD basic restriction. A cluster-based phase retrieval method did not converge on the measured data. At city scale, adjoint (receiver-to-source) ray tracing, image-informed material mapping, and the closed-form surface law were used to compute route-level whole-body Specific Absorption Rate (SAR) at 163 observation points across ten cities at 15 GHz. Route-median SAR differed by a factor of 14.31 across routes. The ten-route calculation took 314 s on a single GPU. The city-scale study includes internal cross-checks (the maximum adjoint-to-Sionna difference is 0.0344 dB) but has no field measurement validation. An outdoor measurement campaign is future work.

7.2 Comparison of methods

This thesis presents a set of computational *routes* with composable components, from a wireless deployment to a compliance quantity. Each route combines an exposure environment, a propagation method, an interface at the body boundary, and a body solver. Fig. 7.1 shows these routes as a graph. The angular electromagnetic field (amplitude, phase, polarization, and direction) is preserved in two interface objects: the far-field path list and the Huygens box. The methods from Fig. 1.7 list the computational costs (from ms to hours) of the routes in this graph.

All four pairings of interface and body solver have been demonstrated. The path list is the input to FDTD in Chapter 2 (one plane wave per direction) and to the surface law in Chapter 5 (incoherent and coherent multipath) and Chapter 6 (city scale). The Huygens box is the input to FDTD in Chapters 3, 4, and 6 (anechoic validation) and to the surface law in Chapter 6 (stairwell exposure).

Table 7.1 compares the cost, validation anchor, and regime of each configuration. The end-to-end error can be decomposed into contributions from each step. The propagation step is the largest source of error: the stairwell model under-predicts the median power by ~ 1.9 dB, with beat-spectrum correlation $+0.55$ to $+0.79$. The interface step (Huygens box at $\leq \lambda/2$ sampling) adds negligible error. The body-coupling step is small: the surface law matches FDTD within ratios of 1.01–1.03, and FDTD itself matches the anechoic measurement at 17% NMAE. Tissue-property uncertainty is $\pm 7\%$. In realistic environments, the propagation error is the largest term. However, both propagation and body-coupling errors are small compared to the >50 dB margins between the computed exposure and the limits.

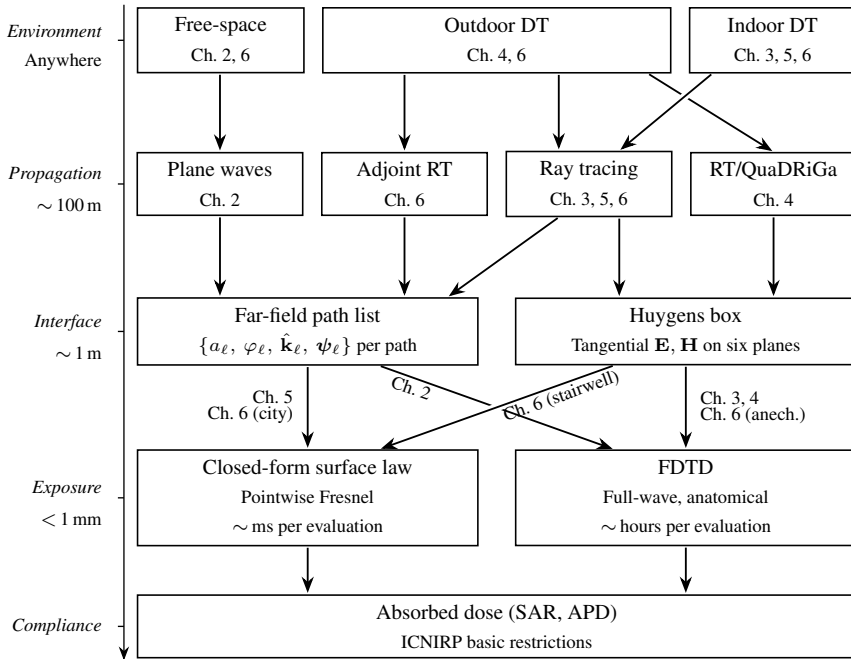


Figure 7.1: Every *route* from a wireless deployment to a dosimetric quantity proposed in this thesis. Each exposure environment is modeled by one or more propagation methods. DT refers to Digital Twin. Arrows from propagation to exposure represent the angular electromagnetic field (amplitude, phase, direction, polarization) passed through one of two interfaces: a far-field path list or a Huygens box. Either interface is the input to either body solver; chapter tags mark the routes. The methods from Fig. 1.7 order these routes by computational cost.

From this decomposition, the appropriate method for each type of question is clear. Guideline research that concerns children, basic restrictions, or tissue detail requires FDTD (Chapter 2). Site-specific compliance assessment requires the hybrid method (Chapters 3 and 4) or the calibrated-twin route (Chapter 6). Network optimization and city- or population-scale studies require the closed-form operator, which is differentiable and evaluated in milliseconds (Chapter 5).

7.3 Main findings

We summarize the main findings in four key points.

First, distributed and cell-free MaMIMO architectures produce lower peak exposure than collocated deployments at equal total radiated power. This result holds indoors (factor 2–3 at 3.5 and 28 GHz, Chapter 3) and outdoors (~20 dB dynamic-range reduction, Chapter 4), across sub-6 GHz and mmWave frequencies.

Table 7.1: Comparison of exposure-assessment configurations proposed in this thesis. Each row combines a propagation method, an interface at the body boundary, and a body solver. NMAE refers to Normalised Mean Absolute Error.

Configuration	Ch.	Cost	Validated against	Regime
Plane wave $\rightarrow$ FDTD	2	hours ($\propto f^4$)	Literature FDTD ($\leq 2\%$)	Any f , gold standard
RT $\rightarrow$ box $\rightarrow$ FDTD (in-door)	3	min-hours	Ch. 2; anechoic scan (17% NMAE)	Site-specific indoor
RT + QuaDRiGa $\rightarrow$ box $\rightarrow$ FDTD (outdoor)	4	min-hours	Ch. 3; RT cross-check	Site-specific outdoor
Paths $\rightarrow$ incoherent law	5	ms	Mie, FDTD (1–3%), 108 volunteers	Far field, ≥ 6 GHz
Paths $\rightarrow$ coherent operator	5	ms	Incoherent limit + FDTD	Far field, beamforming
Twin $\rightarrow$ box $\rightarrow$ point-wise law	6	31 s / 22 pos.	Stairwell scans (+0.55–0.79)	Indoor, near field
Adjoint RT $\rightarrow$ law (city)	6	314 s / 10 cities	Internal cross-checks	City scale

The mechanism is that many distributed access points spread the radiated power, which limits the worst-case incident field at any single location.

Second, the gap between reference levels and basic restrictions depends on frequency, body geometry, and the multipath environment. In realistic multipath, reference levels are conservative for adults: basic-restriction quantities are 5–10 dB below the limits when reference levels are at their limits (Chapter 3). However, reference levels are not conservative for children and for auto-induced exposure near 2140 MHz, 3500 MHz, and 7 GHz (Chapter 2). Reference levels are derived from basic restrictions under worst-case assumptions and do not account for this variation. The closed-form operator of Chapter 5 evaluates basic restrictions directly.

Third, for the considered realistic scenarios, the exposure is far below the ICNIRP limits. The highest indoor exposure is $\leq 4\%$ of the limits (Chapter 3). The outdoor maximum is $< 0.05\%$ (Helsinki, 320 W, Chapter 4). The stairwell exposure is over 54 dB below the general-public APD basic restriction (Chapter 6). At city scale, route-median SAR differs by a factor of 14.31 across ten cities, but all values remain far below regulatory limits at realistic output powers.

Fourth, coherent focusing increases with array size. The hot-spot gain reaches 12 dB on top of the beamforming gain, with a full-width at half-maximum of 0.44λ along the propagation axis (Chapter 4). The hot-spot gain is theoretically unbounded in element count. Exposure-constrained beamforming (Chapter 5) is a network-level solution: the closed-form operator evaluates all applicable ICNIRP basic restrictions from the same ray-traced paths that determine the channel, at a cost that is independent of array size.

7.4 Future work

Two thesis-level limitations apply beyond the per-method limitations discussed in the relevant chapters. Every chapter evaluates exposure at a single time instant. Real exposure under the ICNIRP guidelines is averaged over 30 minutes for whole-body quantities and six minutes for local quantities. During these intervals, the beam schedule, user traffic and body position all change. The gap between the instantaneous peak computed in this thesis and the time-averaged quantity that the guidelines regulate is not quantified. This limitation applies to all methods: FDTD (Chapter 2), the hybrid method (Chapters 3 and 4), the closed-form operator (Chapter 5), and the measurement-validated scenarios (Chapter 6). Moreover, the data realism is fundamentally constrained by industry access. Device and base-station antenna patterns are proprietary. All deployments are modeled from public data. The closed-form operator requires only the propagation paths, so its accuracy depends on the fidelity of these paths. The numerical dosimetry community would benefit from open-sourcing some of this proprietary data.

Six themes for future work follow from these limitations and from the directions identified in the individual chapters.

Near field and devices

The Huygens-box coupling used in Chapter 6 accounts for the illumination variation across the body indoors, but a true near-field operator that resolves depth and increases with aperture size remains to be developed. Closed-form uplink pre-compliance for on-body devices is a natural extension: at mmWave frequencies the far-field distance is on the order of centimeters, so the device antenna pattern maps directly onto the body surface. A body-aware channel sensitivity study is needed to quantify how body blockage and scattering affect the signal channel used by the beamformer.

Multi-body and network integration

The single-user beamformer of Chapter 5 extends to multi-body exposure-constrained beamforming across an occupied environment, with one per-body operator on the shared paths. Because the operator is differentiable in every input, gradients of the regulated quantities can propagate to antenna positions, orientations, and beam codebooks, which is useful for exposure-aware network design. Real-time dosimetry in the network loop is a potential application: the cost per evaluation is below 10 ms, well below the timescale on which a person's pose changes.

Measurement

The first priority is an outdoor city-scale campaign with source calibration and body-worn exposimeters to validate the directional field before body coupling. A higher-fidelity Digital Twin (DT), with denser measurement sampling and refined material parameters, is likely needed to reduce the remaining propagation error.

Validation at Frequency Range 3 (FR3) and sub-THz frequencies is needed to match the frequency range of the closed-form law.

Population scale

The current results use a small number of body models and a fixed standing posture. Many bodies, postures, ages, and body compositions are needed for population-level exposure distributions. Several routes at each city site can quantify route-selection variation. Multi-frequency city runs and epidemiological input, for example through the GOLIAT project, are natural extensions.

Regulation

The inconsistency between reference levels and basic restrictions found in Chapter 2 is a reason for direct basic-restriction assessment in the field. Direct assessment is practical with the closed-form operator. The 7.125–8.4 GHz band is on the WRC-27 agenda. Compliance assessment at this band should include child phantoms, given the reference-level exceedances observed in Chapter 2.

Validation at city scale

The pipeline is validated at Frequency Range 2 (FR2; 26 and 28 GHz) but the city-scale application uses FR3 (15 GHz). The city-scale study has no outdoor field measurement validation, as matching simulations and measurements deterministically is a long-standing challenge in the wider wireless propagation literature. It uses one body model (Duke), one frequency, and one source distribution. An outdoor measurement campaign with source calibration and body-worn exposimeters is needed to close this gap.

The computational path from a wireless deployment to the absorbed dose in a human body is now complete: full-wave where fidelity is needed, closed-form where scale is needed, and measured where measurement was possible. The methods and data produced in this thesis are available for compliance assessment, network design, and epidemiological studies of current and future wireless networks.