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Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (frequency range of 6 GHz to 300 GHz) –

Part 2: Computational procedure

Évaluation de la densité de puissance de l'exposition humaine aux champs radiofréquences provenant de dispositifs sans fil à proximité immédiate de la tête et du corps (plage de fréquences de 6 GHz à 300 GHz) –

Partie 2: Procédure de calcul



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IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland
Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue
New York, NY 10016-5997
United States of America
stds.ipr@ieee.org
www.ieee.org

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CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
1 Scope.....	9
2 Normative references	9
3 Terms and definitions	10
3.1 Exposure metrics and parameters.....	10
3.2 Spatial, physical, and geometrical parameters associated with exposure metrics.....	11
3.3 Test device technical operating and antenna parameters	13
3.4 Computational parameters	13
3.5 Uncertainty parameters.....	14
4 Symbols and abbreviated terms.....	14
4.1 Symbols.....	14
4.1.1 Physical quantities.....	14
4.1.2 Constants	15
4.2 Abbreviated terms.....	15
5 Overview and application of this document	16
5.1 Overview of the numerical evaluation.....	16
5.2 Application of this document	17
5.3 Stipulations.....	18
6 Requirements on the numerical software	18
7 Model development and validation.....	19
7.1 General.....	19
7.2 Development of the numerical model of the DUT.....	19
7.3 Power normalization	20
7.4 Requirements on the experimental test equipment for model validation.....	22
7.4.1 General	22
7.4.2 Ambient conditions and device holder.....	23
7.4.3 Power measurement.....	23
7.5 Testing configurations for the validation of the DUT model.....	24
7.5.1 General	24
7.5.2 Tests to be performed.....	24
7.5.3 Determining the validity of the DUT model	25
7.5.4 Test reduction for additional DUTs.....	25
8 Power density computation and averaging.....	26
8.1 Evaluation surface	26
8.2 Tests to be performed and DUT configurations	26
8.2.1 General	26
8.2.2 Devices with a single radiating element or with multiple elements that do not operate simultaneously	27
8.2.3 Devices with antenna arrays or sub-arrays	27
8.2.4 Devices with multiple antennas or multiple transmitters	28
8.3 Considerations on the evaluation surface and dimensions of the computational domain	29
8.4 Averaging of power density on an evaluation surface	29
8.4.1 General	29
8.4.2 Construction of the averaging area on an evaluation surface.....	30

8.5	Computation of sPD by integration of the Poynting vector.....	31
8.5.1	General	31
8.5.2	Surface-normal propagation-direction power density into the evaluation surface, sPD_{n+}	31
8.5.3	Total propagating power density into the evaluation surface, sPD_{tot+}	32
8.5.4	Total power density directed into the phantom considering near-field exposure, sPD_{mod+}	32
8.6	Software	33
9	Uncertainty evaluation	33
9.1	General.....	33
9.2	Uncertainty of the sPD and of the $mpsPD$ due to the computational parameters	33
9.2.1	Uncertainty contributions due to the computational parameters	33
9.2.2	Mesh resolution	34
9.2.3	Absorbing boundary conditions	35
9.2.4	Power budget	35
9.2.5	Model truncation.....	35
9.2.6	Convergence	35
9.2.7	Dielectric properties.....	36
9.2.8	Lossy conductors.....	36
9.3	Uncertainty contribution of the computational representation of the DUT model	36
9.4	Uncertainty of the maximum exposure evaluation	37
9.5	Uncertainty budget.....	38
10	Reporting	39
Annex A (normative)	Code verification	41
A.1	General.....	41
A.2	Interpolation and superposition of vector field components	41
A.3	Computation of the far-field pattern and the radiated power	43
A.4	Implementation of lossy conductors	43
A.5	Implementation of anisotropic dielectrics.....	46
A.6	Computation of the sPD and $psPD$	47
A.6.1	General	47
A.6.2	Planar surfaces	49
A.6.3	Non-planar surfaces	50
A.7	Implementation of the field extrapolation according to the surface equivalence principle	52
Annex B (informative)	Experimental evaluation of the radiated power	53
B.1	General.....	53
B.2	Direct conducted power measurements.....	53
B.3	Radiated power measurement methods	54
B.4	Information provided by the DUT.....	54
Annex C (normative)	Maximum-exposure evaluation techniques	55
C.1	General.....	55
C.2	Evaluation of EM fields radiated by each antenna element.....	55
C.3	Evaluation of the $mpsPD$ by superposition of individual EM fields	56
C.3.1	General	56
C.3.2	Maximization over the entire codebook by exhaustive search	56
C.3.3	Optimization with fixed total conducted power.....	56

C.3.4	Optimization with fixed power at each port.....	56
Annex D (informative)	Examples of the implementation of power density averaging algorithms.....	58
D.1	Example for the evaluation of the $psPD$ on a planar surface	58
D.1.1	General	58
D.1.2	Evaluation of the $psPD$ by direct construction of the averaging area.....	58
D.1.3	Example for the efficient evaluation of the $psPD$ using an equidistant mesh on the evaluation surface	59
D.2	Example for the evaluation of the $psPD$ on a non-planar surface	60
Annex E (informative)	File format for exchange of field data	62
Annex F (informative)	Rationales of the methods applied in IEC/IEEE 63195-1 and this document.....	64
F.1	Frequency range.....	64
F.2	Computation of sPD	64
F.2.1	Application of the Poynting vector for computation of incident power density.....	64
F.2.2	Averaging area	65
Annex G (informative)	Square averaging area on non-planar evaluation surfaces	66
G.1	General.....	66
G.2	Example implementation for the evaluation of the $psPD$ on a non-planar surface using square-shaped averaging area.....	66
Annex H (informative)	Validation of the maximum-exposure evaluation techniques	67
H.1	General.....	67
H.2	Validation of the exhaustive search.....	67
H.2.1	Validation of the exhaustive search	67
H.2.2	Validation using reconstruction method	67
H.2.3	Validation of optimization with fixed total conducted power or with fixed power at each port.....	67
H.2.4	Validation of the maximum-exposure evaluation of measurement results	67
H.3	Example validation source for maximum-exposure evaluation validation	68
H.3.1	Description	68
H.3.2	Positioning.....	70
H.3.3	Nominal codebook, uncertainty and conducted power P_R	71
H.3.4	Target values.....	71
Annex I (normative)	Supplemental files and their checksums	73
Bibliography		74
Figure 1	– Overview of the numerical power density evaluation procedure.....	17
Figure 2	– Power reference planes	22
Figure 3	– Example for configurations of radiating elements as different antenna sub-arrays on the same DUT	27
Figure 4	– Flow chart for the evaluation of power density for DUTs with antenna arrays or sub-arrays as described in 8.2.3	28
Figure 5	– Example of the construction of the averaging area within a sphere with fixed radius according to 8.4	31
Figure A.1	– Configuration of three $\lambda/2$ dipoles, D_1 , D_2 , and D_3 , for the evaluation of the interpolation and superposition of the electric field and magnetic field components.....	42
Figure A.2	– R320 waveguide	45

Figure A.3 – Cross section of the R320 waveguide showing the locations of the E_y components to be recorded.....	46
Figure A.4 – $S_i(x,y)$ computed with Formula (A.4) for the six parameter sets of Table A.6 normalized to their maxima	49
Figure A.5 – Cross sections of the symmetric quarters of the testing geometries (SAR Stars) for the benchmarking of the power density averaging algorithm.....	51
Figure A.6 – Areas for the computation of the sPD on a cone of the SAR Star.....	51
Figure D.1 – Rotated averaging area on the discretized evaluation surface (base mesh)	60
Figure D.2 – Reduction of the area of triangles that are partially included in the averaging sphere	61
Figure H.1 – Main dimensions of patch array stencil	69
Figure H.2 – Main dimensions of the validation device, including polypropylene casing	70
Figure H.3 – Validation device with SAM head in the tilt position	70
Figure H.4 – Validation device with SAM head in the touch position.....	71
Table 1 – Budget of the uncertainty contributions of the computational algorithm for the validation setup or testing setup	34
Table 2 – Budget of the uncertainty of the developed model of the DUT	37
Table 3 – Computational uncertainty budget	38
Table A.1 – Interpolation and superposition of vector field components; maximum permissible deviation from the reference results is 10 %	42
Table A.2 – Computation of P_R ; maximum permissible deviation from the reference results is 10 % for the radiated power and for the electric field amplitude of the far-field pattern	43
Table A.3 – Minimum fine and coarse mesh step for used method	46
Table A.4 – Results of the evaluation of the computational dispersion characteristics	46
Table A.5 – Results of the evaluation of the representation of anisotropic dielectrics	47
Table A.6 – Parameters for the incident power density distribution of Formula (A.4)	48
Table B.1 – Comparison of the experimental methods for the evaluation of the radiated power	53
Table H.1 – Main dimensions for the patch array stencil	68
Table H.2 – Main dimensions of the validation device	68
Table H.3 – Target values for validation device with the nominal codebook.....	72
Table H.4 – Target values for validation device with infinite codebook	72

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ASSESSMENT OF POWER DENSITY OF HUMAN EXPOSURE TO RADIO FREQUENCY FIELDS FROM WIRELESS DEVICES IN CLOSE PROXIMITY TO THE HEAD AND BODY (FREQUENCY RANGE OF 6 GHz TO 300 GHz) –

Part 2: Computational procedure

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This document is published as an IEC/IEEE Dual Logo standard.

This publication contains supplemental files that are required for the code verification according to Annex A. Download links and checksums for these files can be found in Annex I.

The text of this International Standard is based on the following IEC documents:

Draft	Report on voting
106/564/FDIS	106/569/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with the rules given in the ISO/IEC Directives, Part 2, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC/IEEE 63195 series, published under the general title *Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body*, can be found on the IEC website.

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INTRODUCTION

This document provides a method to evaluate the human exposure from wireless devices using computational methods. This document was developed to provide procedures for the numerical modelling and evaluation of such wireless devices operating close to the head, held in the hand or in front of the face, mounted on the body or embedded in garments. It applies to individual transmitters as well as to transmitters operating simultaneously with other transmitters within a product. The choice of technique, i.e. FDTD or FEM, is optional but can be influenced by the application. The advantages of computational procedures include the capability to provide repeatable, non-intrusive methods for determining exposure in or near an object and without the need for expensive hardware equipment. Device categories covered include but are not limited to mobile telephones, radio transmitters in personal computers, desktop and laptop devices, and multi-band and multi-antenna devices. This document specifies:

- requirements on the numerical software (Clause 5);
- model development and validation (Clause 7);
- power density computation and averaging (Clause 8);
- uncertainty evaluation (Clause 9);
- reporting requirements (Clause 10).

To develop this document, IEC Technical Committee 106 (TC 106) and IEEE International Committee on Electromagnetic Safety (ICES), Technical Committee 34 (TC 34) Subcommittee 1 (SC 1) formed Joint Working Group 11 (JWG 11) on computational methods to assess the power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body.

ASSESSMENT OF POWER DENSITY OF HUMAN EXPOSURE TO RADIO FREQUENCY FIELDS FROM WIRELESS DEVICES IN CLOSE PROXIMITY TO THE HEAD AND BODY (FREQUENCY RANGE OF 6 GHz TO 300 GHz) –

Part 2: Computational procedure

1 Scope

This document specifies computational procedures for conservative and reproducible computations of power density (PD) incident to a human head or body due to radio-frequency (RF) electromagnetic field (EMF) transmitting devices. The computational procedures described are finite-difference time-domain (FDTD) and finite element methods (FEM), which are computational techniques that can be used to determine electromagnetic quantities by solving Maxwell's equations within a specified computational uncertainty. The procedures specified here apply to exposure evaluations for a significant majority of the population during the use of hand-held and body-worn RF transmitting devices. The methods apply to devices that can feature single or multiple transmitters or antennas, and that can be operated with their radiating part or parts at distances up to 200 mm from a human head or body.

This document can be employed to determine conformity with any applicable maximum PD requirements of different types of RF transmitting devices used in close proximity to the head and body, including those combined with other RF transmitting or non-transmitting devices or accessories (e.g. belt-clip), or embedded in garments. The overall applicable frequency range of these protocols and procedures is from 6 GHz to 300 GHz.

The RF transmitting device categories covered in this document include but are not limited to mobile telephones, radio transmitters in personal computers, desktop and laptop devices, and multi-band and multi-antenna devices.

The procedures of this document do not apply to PD evaluation of electromagnetic fields emitted or altered by devices or objects intended to be implanted in the body.

NOTE For the evaluation of the combined exposure from simultaneous transmitters operating on frequencies below 6 GHz, the relevant standards for SAR computation are IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/IEEE 62704-1:2017, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 1: General requirements for using the finite difference time-domain (FDTD) method for SAR calculations*

IEC/IEEE 62704-4:2020, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 4: General requirements for using the finite element method for SAR calculations*

IEC/IEEE 63195-1:2021¹, *Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (frequency range of 6 GHz to 300 GHz) – Part 1: Measurement procedure*

IEEE Std 145, *IEEE Standard for Definitions of Terms for Antennas*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO, IEC, and IEEE maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>
- IEEE Dictionary Online: available at <http://dictionary.ieee.org>

3.1 Exposure metrics and parameters

3.1.1

power density

PD

local power density

function of the complex Poynting vector S at the location r that is integrated over a surface to compute the sPD

Note 1 to entry: Specifications of power density in terms of the integrands of Formula (4), Formula (5), and Formula (8) are provided in 8.5. See also rationales provided in Annex F for the PD specifications of 8.5.

Note 2 to entry: The formula used to compute PD can depend on the applicable exposure guidelines or national regulations.

Note 3 to entry: Power density is also referred to as power flux density.

Note 4 to entry: The associated term incident power density refers to quantity of power per unit area that impinges on the body surface. The incident power density just outside the body surface is used to establish local exposure reference levels, which apply at frequencies above 6 GHz in some jurisdictions.

3.1.2

spatial-average power density

sPD

PD (3.1.1) averaged over a surface of area A_{av}

Note 1 to entry: sPD is a function of the location vector r . It is determined on the evaluation surface, except for the edges where no averaging area can be constructed.

Note 2 to entry: Example averaging area sizes specified in exposure limits are 1 cm² and/or 4 cm².

¹ To be published.

3.1.3**peak spatial-average power density***psPD*global maximum value of all the *sPD* (3.1.2) values on the evaluation surface (3.2.2)Note 1 to entry: *psPD* is given by Formula (1)

$$psPD = \max_r \{sPD(\mathbf{r})\} \quad (1)$$

where *r* is a point on the evaluation surface.

Note 2 to entry: Other local maxima (i.e. secondary peak spatial-average power density values) can exist.

3.1.4**maximized peak spatial-average power density***mpsPD**psPD* (3.1.3) of the excitation vector (3.3.5) that maximizes its value**3.1.5****Poynting vector***S*vector product of the electric field strength *E* and the magnetic field strength *H* of the electromagnetic field at a given point

Note 1 to entry: The flux of the Poynting vector through a closed surface is equal to the electromagnetic power passing through this surface.

Note 2 to entry: For a periodic electromagnetic field, the time average of the Poynting vector is a vector the direction of which, with certain reservations, can be considered as being the direction of propagation of electromagnetic energy and the magnitude of which can be considered as being the average power flux density.

Note 3 to entry: For a sinusoidal wave of angular frequency ω , the complex Poynting vector is expressed by Formula (2)

$$\mathbf{S} = \frac{1}{2} \mathbf{E} \times \mathbf{H}^* \quad (2)$$

where *E* and *H* are phasors and the asterisk denotes the complex conjugate.Note 4 to entry: The Poynting vector has units of watt per square metre (W/m²).

[SOURCE: IEC 60050-121:2019, 121-11-66 and IEC 60050-705:1995, 705-02-10, modified – The entries have been combined and rearranged; Note 4 has been added.]

3.1.6**conservative estimate**

<of exposure> estimate of the exposure, including uncertainties as specified in this document, representative of and slightly higher than that expected to occur in the head or body of a significant majority of the human population during intended use of a wireless transmitting device

3.2 Spatial, physical, and geometrical parameters associated with exposure metrics**3.2.1****averaging area***A_{av}*nominal size of the area used for computing *sPD* (3.1.2)Note 1 to entry: On a planar evaluation surface, *sPD* is computed as the ratio of power density (3.1.1) integrated over the averaging area *A_{av}*. On a non-planar evaluation surface, the averaging area indicates the dimensions of the projection of the integration area of the power density on a planar surface.

Note 2 to entry: See details on averaging in 8.4.

3.2.2

evaluation surface

virtual surface for the evaluation of the spatial-average power density (sPD) emitted by a DUT

Note 1 to entry: Typical evaluation surfaces that can be applied in this document are the inner shell of the SAM phantom with an added pinna, or a planar surface with finite or infinite extension.

Note 2 to entry: The evaluation of the $psPD$ (3.1.3) on the evaluation surface should yield a conservative estimate (3.1.6) of the exposure.

Note 3 to entry: In practice, an evaluation surface can be different from a measurement surface or area.

3.2.3

near-field

region encompassed by the reactive near-field and the radiative near-field

Note 1 to entry: See also 3.2.5 and 3.2.4 for definitions of reactive near-field and radiative near-field, respectively.

3.2.4

radiative near-field

region of space between the reactive near-field and the far-field, wherein the predominant components of the electromagnetic field are those that represent a propagation of energy, and wherein the angular field distribution is dependent upon the distance from the antenna

Note 1 to entry: In the radiative near-field, the out-of-phase (i.e. evanescent) component of the electromagnetic field decays, and the in-phase (i.e. propagating) component of the electromagnetic field emerges.

3.2.5

reactive near-field

region of space immediately surrounding an antenna, where the predominant components of the electric field and magnetic field are those that represent an exchange of reactive energy between the antenna and the surrounding medium, and where electric field and magnetic field components are 90° out of phase

[SOURCE: IEC 60050-712:1992, 712-02-01, modified – In the definition, the electric field and magnetic field component phase difference has been added.]

3.2.6

far-field

region of the electromagnetic field of an antenna where the predominant components of the field are those that represent energy propagation, the angular field distribution is essentially independent of the distance from the geometrical centre of the antenna, and the ratio of predominant electric field and magnetic field components is constant and equal to the wave impedance of 377 Ω

[SOURCE: IEC 60050-712:1992, 712-02-02, modified – In the definition, the distance to geometrical centre of the antenna has been clarified, and a phrase on the ratio of the electric and magnetic components has been added.]

3.3 Test device technical operating and antenna parameters

3.3.1

channel

RF channel

part of the frequency spectrum intended to be used for the transmission of signals and which may be defined by two specified limits, or by its centre frequency and the associated bandwidth, or by any equivalent indication

Note 1 to entry: The number of RF channels and the corresponding channel bandwidth can vary among individual wireless technologies and is subject to national frequency allocations. For the purposes of this document, PD computations are performed at specific channels; for example, the high, middle, and low channels of the transmission band.

3.3.2

antenna sub-array

subset of radiating elements in an array that operate collectively

Note 1 to entry: Antenna elements can be used separately by two or more sub-arrays.

3.3.3

array

<of antennas> antenna comprised of a number of generally identical radiating elements, arranged, oriented and excited to obtain a prescribed radiation pattern

3.3.4

codebook

set of all possible excitation vectors

3.3.5

excitation vector

vector of all phasors that represent the input signal to an antenna array or sub-array

Note 1 to entry: The entries of a codebook are excitation vectors.

3.3.6

module

sub-assembly

self-contained RF transceiver that only needs power and communication to its host through a connector, ball grid arrays or pins and is designed to be incorporated into a final product

3.4 Computational parameters

3.4.1

computational domain

set of all spatial locations at which the electric field or magnetic field is computed by a mathematical equation or a computational algorithm

3.4.2

lumped source

source with an inner impedance which is applied to an electric field component on an edge of the computational mesh

3.4.3

perfect electric conductor

PEC

material with infinite electrical conductivity which does not dissipate any energy

3.4.4

surface equivalence principle

theorem that states that sources within a closed region can be replaced by substitute sources on the region surface giving rise to the same field outside the enclosed regions

Note 1 to entry: Details can be found in [1].

3.5 Uncertainty parameters

3.5.1

uncertainty

confidence range of the evaluated value

3.5.2

standard uncertainty

estimated standard deviation of a measurement or computation result, equal to the positive square root of the estimated variance

3.5.3

combined uncertainty

estimated standard deviation of the measurement or computation result obtained by combining the individual standard uncertainties of both Type A and Type B evaluations using the "root-sum-square" method of combining standard deviations that are obtained by taking the positive square root of the estimated variances

3.5.4

expanded uncertainty

quantity defining an interval about the result of a measurement or computation that is expected to encompass a distribution of values within a specified confidence interval that can reasonably be attributed to the measurand

3.5.5

uncertainty evaluation

evaluation of uncertainty by the statistical analysis of series of observations (Type A) or by other means (Type B)

4 Symbols and abbreviated terms

4.1 Symbols

4.1.1 Physical quantities

The internationally accepted SI units are used throughout the document.

Symbol	Quantity	Unit	Dimensions
a	attenuation coefficient	reciprocal metre	1/m
P	power	watt	W
J	current density	ampere per square metre	A/m ²
σ	electric conductivity	siemens per metre	S/m
E	electric field strength	volt per metre	V/m
f	frequency	hertz	Hz
S	Poynting vector	watt per square metre	W/m ²
H	magnetic field strength	ampere per metre	A/m
ρ	mass density	kilogram per cubic metre	kg/m ³
δ	penetration depth	metre	m

Symbol	Quantity	Unit	Dimensions
μ	permeability	henry per metre	H/m
sPD	spatial-average power density	watt per square metre	W/m ²
sPD_{n+}	spatial-average power density, surface normal, directed into the phantom	watt per square metre	W/m ²
sPD_{tot+}	spatial-average power density, total, directed into the phantom	watt per square metre	W/m ²
sPD_{mod+}	spatial-average power density, modulus	watt per square metre	W/m ²
$psPD$	peak spatial-average power density	watt per square metre	W/m ²
$mpsPD$	maximized peak spatial-average power density	watt per square metre	W/m ²
c_h	specific heat capacity	joule per kilogram per kelvin	J/(kg K)
ε	permittivity	farad per metre	F/m
SAR	specific absorption rate	watt per kilogram	W/kg
T	temperature	kelvin	K
λ	wavelength	metre	m

NOTE In this document, temperature is quantified in degrees Celsius, as defined by: $T (^{\circ}\text{C}) = T (\text{K}) - 273,15$.

4.1.2 Constants

Symbol	Physical constant	Magnitude
c	speed of light in vacuum	$2,998 \times 10^8$ m/s
η_0	characteristic impedance of free space	376,73 Ω
ε_0	permittivity of free space	$8,854 \times 10^{-12}$ F/m
μ_0	permeability of free space	$4\pi \times 10^{-7}$ H/m

4.2 Abbreviated terms

ABC	absorbing boundary condition
CAD	computer aided design
DFT	discrete Fourier transform
DUT	device under test
EIRP	equivalent isotropically radiated power
FDTD	finite-difference time-domain
FEM	finite element method
HDF5	hierarchical data format Version 5
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IF	intermediate frequency
MEE	maximum exposure evaluation (technique)
P_A	power available from the generator
P_M	power to matched transmission line
P_O	power accepted by the antenna

P_R	power radiated by the antenna
PD	power density
PEC	perfect electric conductor
RF	radio frequency
SAM	specific anthropomorphic mannequin
SAR	specific absorption rate
SI	système international
STL	stereolithography

5 Overview and application of this document

5.1 Overview of the numerical evaluation

This document specifies procedures for the evaluation of the spatial-average electromagnetic power density of wireless communication devices operating at frequencies from 6 GHz to 300 GHz using computational methods applying the finite-difference time-domain (FDTD) technique or the finite element method (FEM). The evaluation of the power density is carried out in different steps, which are the following:

- a) determination of the evaluation required;
- b) selection of the methodology and of an applicable, verified computational software package;
- c) definition of the tests to be performed;
- d) development and validation of the numerical DUT model;
- e) evaluation of the power density;
- f) quantification of the uncertainty.

Figure 1 gives a high-level overview of these steps and references the subclauses that describe them in detail.

Clause 6 to Clause 10 present the procedures that are required for the numerical power density evaluation of a DUT. The evaluation shall be carried out with software that is verified for the correct technical implementation of this document. The complementary procedures that describe the verification of the numerical computation software and that are mainly relevant for the software manufacturers are given in the annexes. Software may alternatively be verified by the user of this document, e.g. as part of the power density evaluation of a DUT, according to these methods.

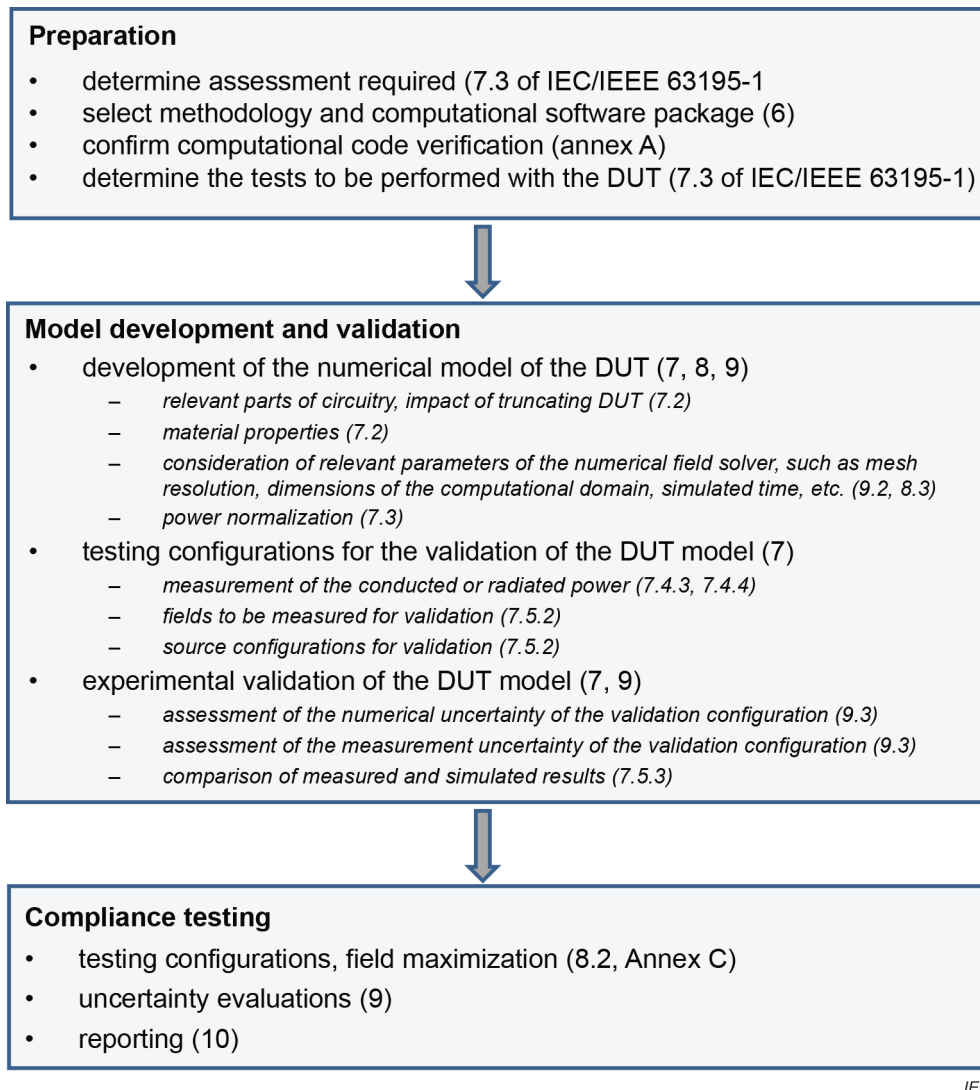


Figure 1 – Overview of the numerical power density evaluation procedure

5.2 Application of this document

This document and IEC/IEEE 63195-1 were developed in parallel in two joint working groups of IEC and IEEE to prepare procedures for conformity evaluation to exposure limits on the incident power density under particular consideration of the exposure from wireless devices of the new fifth generation (5G) mobile technology operating in a frequency range from 6 GHz to 300 GHz. This document specifies computational procedures, and IEC/IEEE 63195-1 specifies measurement procedures.

After the fundamental work on the measurement procedures for conformity evaluation at frequencies above 10 GHz had been documented in IEC TR 63170:2018 [2]², both IEC/IEEE 63195-1 and this document were developed in a comparatively short time period of two years. In parallel, the ICNIRP and TC95 of the IEEE ICES revised their exposure guidelines and included new basic restrictions and reference levels for the frequency range of 6 GHz and above. These are based on the incident and absorbed/epithelial power density or incident power density, respectively, averaged over a square area of 1 cm² or 4 cm².

² Numbers in square brackets refer to the Bibliography.

IEC/IEEE 63195-1 contains all relevant specifications for the application of measurement procedures for conformity evaluation. While it can be applied independently from this document, it refers to the post processing methods for power density averaging and maximization of the incident power density that are common to both IEC/IEEE 63195-1 and this document, but are specified only in this document. Likewise, computational conformity evaluation is described in this document. For validations of numerical modelling results by measurements, the methods of IEC/IEEE 63195-1 are required.

5.3 Stipulations

Due to the constraints on the time available for the development of IEC/IEEE 63195-1 and this document, practical options needed to be found regarding the interpretation of the new exposure guidelines for the evaluation of the conformity with the new limits. These concern the construction of the averaging area and the computation of the spatial-average power density on this averaging area. Regarding the computation of the spatial-average power density, different methods are specified with the objectives to warrant compatibility with exposure evaluations obtained according to IEC TR 63170:2018 [2] and to consider exposure conditions other than perpendicular incidence in the far-field. Annex F discusses the options and their rationales.

These options do not impair the applicability of the methods specified in IEC/IEEE 63195-1 and this document for the conformity evaluation with the reference levels specified in the exposure guidelines.

6 Requirements on the numerical software

This Clause 6 describes the characteristics and features of the numerical software to be used for the computation of the peak spatial-average power density (p_{sPD}) that are required for both the application of the software according to Clause 7, Clause 8, and Clause 9, and for the verification of its correct implementation according to Annex A. The following characteristics and features of the numerical software are required:

- a) Maxwell's equations solver based on FDTD or FEM in the frequency domain according to the definitions in IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020, respectively;
- b) modelling environment and mesh generator for the representation of the electrically relevant parts of the DUT and of nearby objects for the rendering of its electric and magnetic fields at specifiable geometrical resolution limited only by the available computer memory;
- c) representation of isotropic perfect electric conductors;
- d) representation of isotropic dielectric materials with relative permittivities $\varepsilon_r \geq 1$ and electric conductivities $\sigma \geq 0$;
- e) representation of uniaxial anisotropic dielectric materials with relative permittivities $\varepsilon_r \geq 1$ and electric conductivities $\sigma \geq 0$;
- f) isotropic electric losses $\sigma < \infty$ in metallic conductors that are represented as thin sheets or filaments;
- g) interpolation of the frequency domain computation results to specifiable points within the computational domain;
- h) superposition of the computed E -vector and H -vector fields in the frequency domain of a specifiable number of computation results using specifiable complex scaling factors, e.g. for the evaluation of the beam steering of phased array antennas;
- i) computation of the dissipated power considering losses in dielectrics and in metallic conductors for a specifiable number of superimposed computation results on specifiable meshes;
- j) superposition of the far-field patterns of a specifiable number of computation results using specifiable complex scaling factors including the evaluation of P_R , e.g. for the evaluation of the beam steering of phased array antennas;

- k) computation of the *sPD* and *psPD* according to 8.5;
- l) computation of the *mpSPD* according to Annex C.

Extensions of FDTD or FEM that include the required characteristics and features a) through l) but provide additional features may be applied provided that they have been fully validated and that their implementation has been verified. These alternative methods shall provide at least the same accuracy as FDTD or FEM methods specified in IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020. The finite integration technique (FIT) in the time domain can be regarded as an extension of FDTD in this context.

NOTE 1 IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020 specify procedures to determine the peak spatial specific absorption rate in the human body using computational methods.

NOTE 2 IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020 cover the application of FDTD and FEM in the frequency range from 30 MHz to 6 GHz. In addition to the code verification described in the two standards, there is a large body of scientific literature that validates the two numerical methods for exposure evaluation in this frequency range. For the extended frequency range up to 300 GHz that is covered in this document, there is little literature available that demonstrates the validity of the two methods. Application examples for this frequency range can be found, e.g. in [3]. In general, FDTD and FEM can be considered as intrinsically frequency independent. If the discretization of the computational domain and the geometry to be computed appropriately consider the conventional discretization criteria, the methods can be expected to work with the same accuracy as in the frequency ranges for which experimental validation has been done. Appropriate discretization of the computational domain and the geometry is asserted by the uncertainty evaluation (Clause 9).

The numerical software may compute electric and magnetic fields outside the computational domain using the surface equivalence principle if all sources and parts of the DUT are contained in the computational domain (8.3). If the software implements field computation using the surface equivalence principle, it shall be validated according to Clause A.7.

7 Model development and validation

7.1 General

In experimental power density evaluation, the unmodified DUT is evaluated according to a standardized protocol using measurement equipment with known uncertainty contributions. Numerical computations of a wireless device are more flexible with respect to the tests to be performed or the modelling of real-world operation conditions, or may even be necessary where experimental evaluation is overly cumbersome or even technically impossible. An essential requirement on the application of numerical methods for power density evaluation with respect to exposure limits is the validation of the numerical model of the DUT using experimental methods. The experimental validation may be carried out in a configuration that is technically simpler than the full evaluations for DUT according to IEC/IEEE 63195-1:2021. Hence, an appropriately validated DUT model can be evaluated numerically in a large number of tests to be performed thereby reducing the overall effort to demonstrate conformity. The requirements and recommendations on DUT modelling and validation, testing equipment and tests to be performed are specified in 7.2, 7.3, 7.4, and 7.5. The evaluation of the uncertainty of results obtained with the applied methods is described in Clause 9.

7.2 Development of the numerical model of the DUT

The development of a numerical model of a DUT for power density evaluation requires a large number of decisions on the level of detail to be represented in the computational domain. Because of the large number of modern devices and the high level of technical innovations in the field, generalized guidelines for the model development cannot be given. In the following, the steps for the development of the DUT model are described.

- a) The model of the DUT should be based on its original CAD data in order to avoid errors or inaccuracies when modelling dielectrics or conductors.

NOTE 1 The development of a numerical model of the DUT based on its CAD data can require individual simplifications or extensions of the available data, such that specific requirements on the CAD data and on the data-importing procedure cannot be made here. The verification of the numerical model according to 7.5 is regarded as an adequate demonstration that the model agrees with the original DUT for the purpose of this document.

- b) All conducting parts shall be integrated into the CAD model because even conductors that are far away from the antenna may couple parasitically and act as radiators. Particular considerations apply if device truncation is used (see step g) and 9.2.5).
- c) The dielectric properties of all major parts in the environment of radiators and RF transmission lines should be modelled correctly considering frequency dependency. References for the dielectric properties should be documented as far as available.
- d) Anisotropic dielectrics should be included in the DUT model if they are relevant for its RF characteristics.
- e) Metallic losses should be included in the DUT model if they are relevant for its RF characteristics or for power normalization.
- f) Modelling of the feeding or matching networks is required if the fields of these networks are not confined in a closed environment. Otherwise, lumped sources can be placed directly at the antenna feed-point. Computations of handheld devices with integrated multiband antennas have shown that it is often difficult to obtain good agreement of the computed feed-point impedance with measurement data. Nevertheless, the normalization of the exposure evaluation results to P_R yields satisfactory accuracy [4].
- g) The computer system should have sufficient computational resources (working memory, processors, storage) to compute the entire DUT model and the evaluation surface. Under some circumstances, a DUT model may be truncated. However, the reactive fields of the model should not be truncated. This shall be demonstrated by comparison of the input reflection coefficients of the antenna or the elements of the antenna array or by identification of the volume storing the reactive energy of the DUT. The latter may be identified by comparison of the ratio of the local electric field and magnetic field amplitudes to the free space wave impedance. The impact of truncating the model shall be indicated in the uncertainty budget.
- h) Guidance on the dimensions of the computational domain can be found in 8.3. The evaluation surface need not be included in the computational domain as the fields on it may be computed using the surface equivalence principle (8.3).
- i) The testing report (Clause 10) shall summarize how these recommendations are considered for the development of the DUT model.

NOTE 2 Additional guidance on the development of the DUT model can be found in 5.4 of IEC/IEEE 62704-3:2017 [5]. Although IEC/IEEE 62704-3:2017 refers to the computation of handheld devices operating at frequencies up to 6 GHz using the FDTD method, 5.4 of IEC/IEEE 62704-3:2017 can be regarded as general enough to provide guidance beyond its original scope, i.e. for devices operating at the frequency range considered in this document and on importing CAD models into computational software using FEM.

7.3 Power normalization

Figure 2 shows the different power reference planes in a DUT and its computational model. The available power at the source P_A is fed to the antenna via a transmission line and/or a matching circuit leading to losses (P_M) due to impedance mismatching and dissipation of the available power in the circuitry resulting in the output power P_O that is accepted by the antenna. Additional losses can occur in the antenna itself, such that the power that is emitted by the DUT is referred to as the radiated power P_R . All power related quantities are defined in IEEE Std 145.

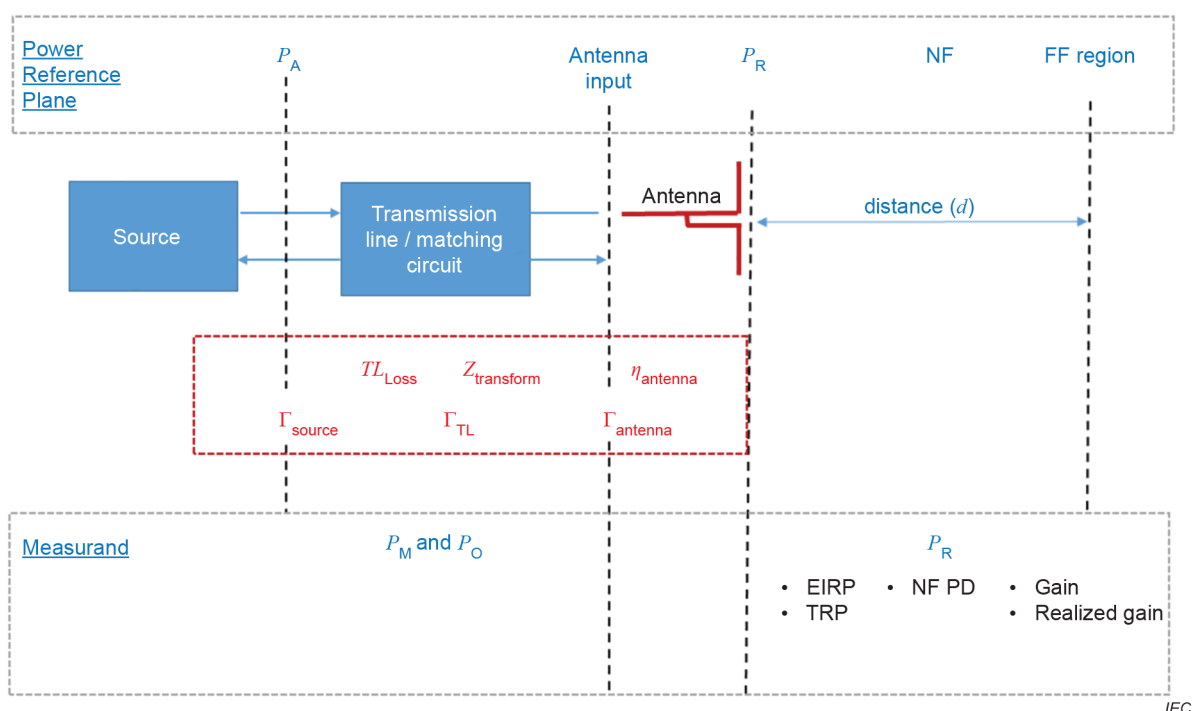
Typically, the computational model of a DUT has a simplified feeding or matching network, which can lead to

- a) specific deviations in the feed-point impedance of the antenna(s),
- b) inaccurate representation of the cross coupling, or
- c) differences in the dielectric or conducted transmission losses.

While these quantities are always available in the computational model, they need not necessarily be an exact representation of those of the actual DUT. Moreover, the feeding or antenna ports of the DUT may not be accessible for conducted power measurements. In the general case, only the EIRP or the P_R of the DUT can be evaluated experimentally to quantify P_R (Annex B).

NOTE Many documents refer to P_R as total radiated power or TRP.

All quantities (Poynting vector, PD , sPD , $psPD$ and $mpsPD$) shall be normalized to the radiated power P_R both for the evaluation of the computational power density according to 8.2 and for the validation of the computational DUT model described in 7.2. If the feeding or antenna ports of the DUT are accessible for conducted power measurements, the radiated power P_R may be computed from P_A or P_M provided that all losses in the DUT are characterized with specified uncertainty.



Key

P_A	available power at the source
P_M	power to matched transmission line
P_O	output power accepted by the antenna
P_R	radiated power
Γ_{source}	reflection coefficient of the source
Γ_{TL}	reflection coefficient of the transmission line or matching circuit
Γ_{antenna}	reflection coefficient of the antenna
η_{antenna}	antenna efficiency
TL_{loss}	power dissipated in the transmission lines
$Z_{\text{transform}}$	transformation matrix of the transmission line or matching circuit
FF	far-field
NF	near-field

NOTE The terms and symbols follow the definitions of Clause 3 and IEEE Std 145.

Figure 2 – Power reference planes

7.4 Requirements on the experimental test equipment for model validation

7.4.1 General

This document specifies only generic requirements on the measurement equipment for model validation with the objective to permit the application of different testing instrumentation. The testing instrumentation shall meet the requirements of Clause 6 of IEC/IEEE 63195-1:2021 that are relevant for the validation of the computational DUT model. Clause 6 of IEC/IEEE 63195-1:2021 specifies the requirements on the following:

- ambient noise and temperature in the laboratory as well as reflections from the laboratory walls;
- dynamic range, cross coupling, physical size and calibration of the field probe or probes;

- calibration of the measurement instrumentation that receives the signals from the probe and prepares it for further processing by a computer system;
- spatial resolution, accuracy and repeatability for scanning single probe systems;
- additional requirements on the spatial resolution concerning multiple probe systems, such as the minimum separation distance;
- reporting requirements of the algorithm that determines the measurement grid
- material properties and reflections from the device holder;
- post processing based on the specifications of 8.5 of this document.

For the experimental evaluation of a DUT with the purpose of model validation, the applied equipment shall enable the following:

- direct evaluation of the Poynting vector in the near-field of the DUT without applying any spatial averaging;
- correlation of the Poynting vector with the P_R of the DUT. based on the measured P_A , P_M or P_R ;
- evaluation of the uncertainty budget of the entire experimental evaluation chain.

7.4.2 Ambient conditions and device holder

Requirements on the RF ambient conditions of the test site and on the device holder shall follow 6.2 and 6.6 of IEC/IEEE 63195-1:2021, respectively, which specify requirements on ambient noise, reflections from the laboratory walls, room temperature constraints and material properties, and permissible reflections from the device holder.

7.4.3 Power measurement

7.4.3.1 Conducted power measurement

If the means are available, the radiated power may be evaluated in terms of the conducted power based on power measurements at the source (amplifier) output (P_A) or at the output of the transmission line (P_M) or matching circuit that is connected to the antenna (P_O) (see Figure 2 for details). For the computation of the radiated power, the quantification of the dielectric or conductive losses in the matching circuit, the antenna, etc., cannot be determined during these measurements; they shall be bracketed, e.g. based on worst-case assumptions or third-party data. In such cases, appropriate rationales and references shall be given.

The applied measurement equipment shall have the following characteristics:

- evaluation of P_O , P_M and the reflection coefficients for the connectors and transmission line impedances of the DUT;
- traceable calibration of the measurement of P_O , P_M and the reflection coefficient for the frequency and modulation of the measured signal of the DUT (Clause B.2);
- uncertainty budget.

7.4.3.2 Radiated power measurement

Radiated power measurements may be based on P_R or EIRP measurements and shall have the following characteristics [6]:

- evaluation of the P_R or EIRP in free space;
- traceable calibration of the P_R measurement for the frequency and modulation of the measured signal of the DUT;
- traceable calibration of the EIRP measurement for the frequency and modulation of the measured signal of the DUT;

- d) traceable evaluation of the antenna gain for the computation of P_R from the EIRP (Clause B.3).

NOTE Antenna gain information can be obtained by computations.

- e) uncertainty budget.

When P_R is measured, it is obtained directly as well as is the three-dimensional EIRP distribution. When only EIRP is measured, e.g. at the peak direction of the transmit beam, P_R can be computed only if the antenna gain and its uncertainty are known.

7.5 Testing configurations for the validation of the DUT model

7.5.1 General

In 7.5.2 and 7.5.3, the required tests and comparison of the computational and experimental results for validation of the DUT model are described. In the tests, the electric field or magnetic field in the near-field of the DUT is evaluated on a surface by choosing configurations specified in 8.2. The PD shall be computed from the Poynting vector or electric or magnetic fields following the specification of the measurement system used for the model validation. All results shall be normalized to P_R . For comparison of measured and computed results, the requirements on the experimental test equipment shall be considered (7.4) and the DUT model shall be validated (7.5.3), and the computational and measurement uncertainty shall be evaluated as described in 9.3.

7.5.2 Tests to be performed

7.5.2.1 Frequency bands and antenna configurations

Computational and experimental evaluation of the near-field of the DUT shall be carried out for the centre frequency of each band at which the DUT can operate. For each antenna, antenna array or sub-array that can be operated or controlled individually, one validation computation and measurement shall be carried out in each applicable frequency band.

7.5.2.2 Evaluation in the near-field

The PD of the DUT shall be measured and computed on a rectilinear grid on a rectangular validation measurement surface according to the following steps.

- a) The distance between the validation measurement surface and the DUT shall be less than or equal to the minimum distance between the DUT and the evaluation surface described in 8.3. If measurements at this distance are not possible, the electric or magnetic fields shall be measured at the minimum possible distance considering the limitations of the applied measurement system and the particular characteristics of the DUT. A rationale for the chosen distance shall be given.
- b) The cross section of the validation measurement surface shall completely include the cross section of the computational domain.
- c) The Poynting vector shall be evaluated at the locations of the measured points, i.e. on the measurement grid. If needed, interpolation methods may be used to determine the computation results at the required locations provided that the contributions of these interpolation methods to the uncertainty of the results are considered in the computational uncertainty U_{sim} .
- d) The measured and computed PD shall be normalized to P_R considering dielectric and conduction losses of the antenna (7.4.3).
- e) The uncertainty of the experimental and computational evaluations of the near-field shall be evaluated according to Clause 9.

7.5.3 Determining the validity of the DUT model

The validation of the computational model of the DUT shall be carried out according to the following steps.

- a) Normalize the experimental sPD to the measured P_R , designated as $v_{\text{ref},n}$.
- b) Determine the measurement uncertainty U_{ref} of the evaluation in the near-field according to Table 3 of Clause 8 of IEC/IEEE 63195-1:2021. Table 3 of Clause 8 of IEC/IEEE 63195-1:2021 summarizes the uncertainty components of the measurement system, the DUT, and the environmental factors. The uncertainty of the power normalization according to the chosen power reference plane (see 7.3, Annex B) shall be considered as an additional entry in the evaluation of U_{ref} according to Table 3 of Clause 8 of IEC/IEEE 63195-1:2021. The combined standard uncertainty shall be evaluated for a 95 % confidence interval ($k = 2$).
- c) Normalize the computational sPD to the computed P_R , designated as $v_{\text{sim},n}$.
- d) Determine the computational uncertainty U_{sim} of the evaluation of the PD according to 9.2.
- e) At every point n at which $v_{\text{ref},n}$ or $v_{\text{sim},n}$ are larger than 5 % of the maximum measured or computed value $\max_n(v_{\text{ref},n}, v_{\text{sim},n})$, validate whether the deviation between the measured value at point n , $v_{\text{ref},n}$ and the computed value $v_{\text{sim},n}$ are within the combined uncertainty of U_{ref} and U_{sim} by evaluating Formula (3):

$$E_n = \sqrt{\frac{(v_{\text{sim},n} - v_{\text{ref},n})^2}{(v_{\text{sim},n} \times U_{\text{sim},k=2})^2 + (v_{\text{ref},n} \times U_{\text{ref},k=2})^2}} \leq 1 \quad (3)$$

The subscript ref in Formula (3) refers to the experimental reference results.

If the deviation is within the combined uncertainty, i.e. if $E_n \leq 1$ for any considered point, the DUT model shall be regarded as valid. If the deviation is not within the expected uncertainty, the DUT model is not valid and shall be revised.

7.5.4 Test reduction for additional DUTs

Similar DUTs may qualify for a reduced model validation where only a subset of DUTs is required to pass the full series of tests specified in 7.5.2. It is possible that applicable national regulations exist. Certain modules may be tested independently. Such validation results can be applicable to other DUTs of a similar type. Examples for models of similar DUTs are devices that share:

- a) the same RF circuitry (transmitter, antenna feed-point, matching components, etc.);
- b) similar dielectric materials with equivalent dielectric properties;
- c) the same antenna and antenna grounding.

If models of similar DUTs are validated with a reduced number of tests or with shared validation results, a rationale shall be given why tests are applicable on the respective modules. This shall be documented separately. Any impact on the uncertainty shall be quantified by additional tests and documented in the uncertainty evaluation (Clause 9).

8 Power density computation and averaging

8.1 Evaluation surface

For frequencies above 6 GHz, guidelines on human exposure to electromagnetic fields specify limits in terms of the power density evaluated as a spatial-average over the averaging area of a certain area A_{av} [7], [8]. In the following, this surface is referred to as the averaging area. This averaging area is part of the evaluation surface. According to 7.2.4 of IEC/IEEE 63195-1:2021, the following different evaluation surfaces are specified:

- a) planar inner surface of the elliptical phantom described in IEC 62209-1528:2020 [9] (7.2.4.2 of IEC/IEEE 63195-1:2021);

NOTE 1 Subclause 7.2.4.2 of IEC/IEEE 63195-1:2021 also specifies the distance between the DUT and the planar evaluation surface.

- b) a planar surface that may be smaller than the inner surface of the elliptical phantom if the application of a smaller surface can be justified;

NOTE 2 A surface smaller than the inner surface of the elliptical phantom can be justified if the DUT or its radiating elements are smaller than the elliptical phantom.

- c) surface of the modified version of the inner shell of the specific anthropomorphic mannequin (SAM) phantom for devices operated at the ear [9] (7.2.4.3 of IEC/IEEE 63195-1:2021);

NOTE 3 Examples for the positioning of the DUT with respect to the evaluation surface or phantom can be found in 7.2.4 of IEC 62209-1528:2020 [9].

- d) specific evaluation surfaces for devices operated at other regions of the body or at regions of the head other than the ear for which the application of one of the above-mentioned averaging areas might not yield an appropriate evaluation of the exposure (7.2.4.4 and 7.2.4.5 of IEC/IEEE 63195-1:2021);

For open evaluation surfaces, such as the surface of the elliptical phantom described in IEC 62209-1528:2020 [9], the surface normal vector points into the direction oriented away from the DUT. For closed evaluation surfaces, such as the modified version of the inner shell of the SAM phantom, the surface normal vector points into the inside of the volume enclosed by the surface.

The coordinates of the inner shell of the SAM phantom with an adapted ear and their surface normal lines are provided as a supplemental file; see Annex I. The spatial-average power density sPD shall be evaluated for all testing configurations described in 8.2. The computation of the $psPD$ according to 8.3, 8.4, 8.5, 8.6 is generally carried out automatically by computational software. The software shall be compliant with the methods specified in 8.6 and shall be verified according to Annex A.

8.2 Tests to be performed and DUT configurations

8.2.1 General

The tests to be performed shall be chosen according to 7.3.1 and 7.3.2 of IEC/IEEE 63195-1:2021 and modelled appropriately. Subclause 7.3.1 of IEC/IEEE 63195-1:2021 specifies the selection of the frequency band, the evaluation surface, and the antenna configurations to be evaluated.

Specific guidance on the evaluation of the $psPD$ of devices with a single radiating element or antenna arrays or sub-arrays (multiple radiating elements) that do not operate simultaneously is specified in 8.2.2. In general, for devices with multiple radiating elements or antenna arrays or sub-arrays, the evaluation of the $mpsPD$ is specified in 8.2.3 and 8.2.4. Figure 3 shows example configurations of radiating elements in different antenna sub-array configurations.

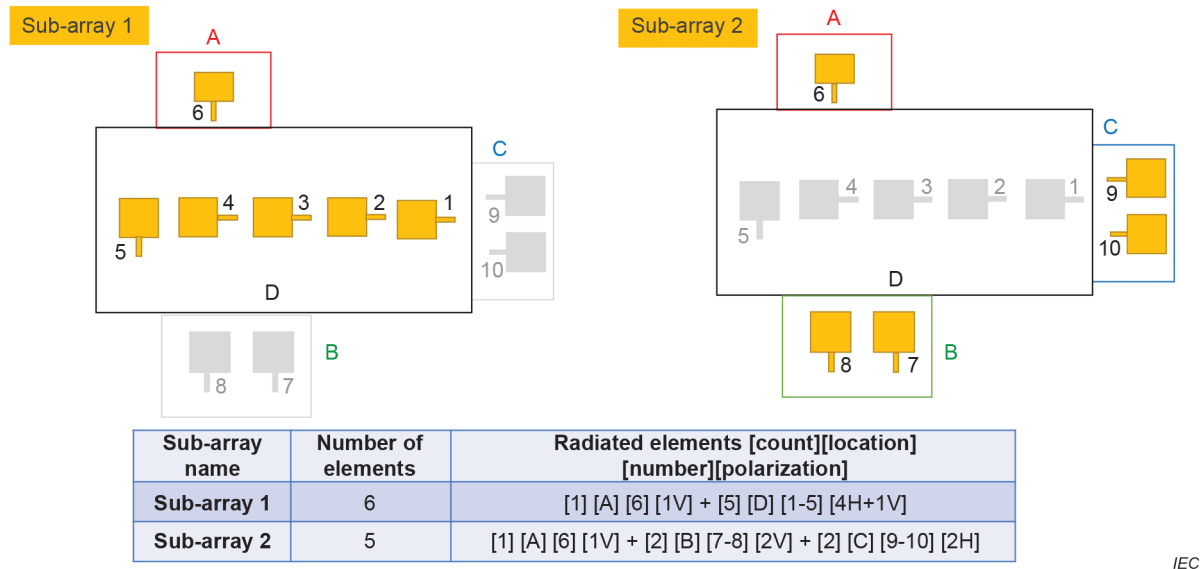


Figure 3 – Example for configurations of radiating elements as different antenna sub-arrays on the same DUT

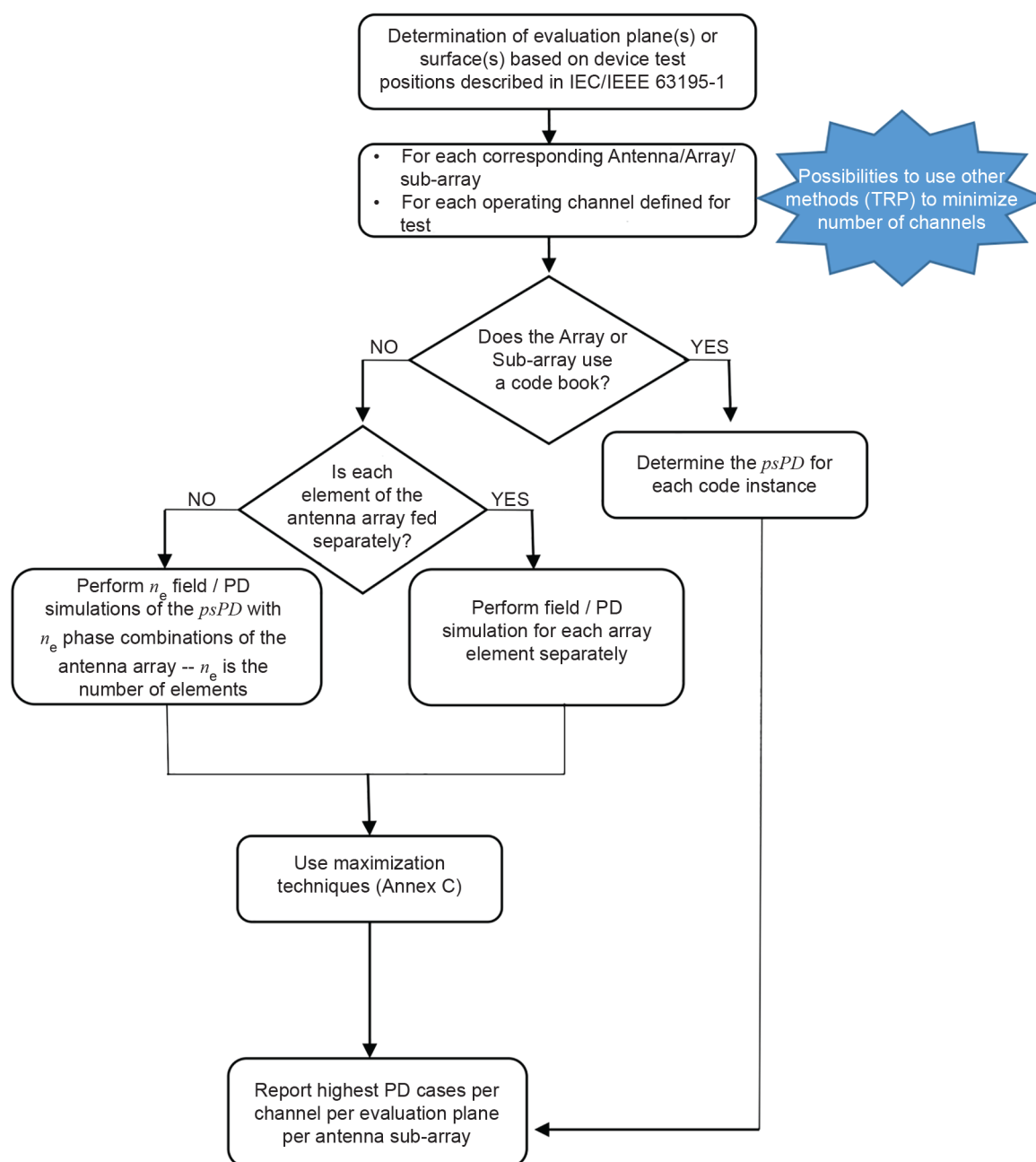
8.2.2 Devices with a single radiating element or with multiple elements that do not operate simultaneously

For DUTs with a single radiating element or antenna arrays or sub-arrays (multiple radiating elements) that do not operate simultaneously, the *psPD* for a particular testing configuration shall be evaluated as follows.

- a) Compute the field distribution of the DUT and compute *psPD* for each active element separately according to 8.3, 8.4, 8.5, 8.6.
- b) Normalize each *psPD* to its P_R (7.3).
- c) Report the *psPD* of all evaluated elements.

8.2.3 Devices with antenna arrays or sub-arrays

The evaluation of the *mpsPD* of devices with antenna arrays or sub-arrays is outlined in Figure 4. The *sPD* shall be computed separately for each RF channel and for each antenna. The *mpsPD* shall then be determined by superimposing the n_e computed fields under application of a maximization technique specified in Annex C.



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Figure 4 – Flow chart for the evaluation of power density for DUTs with antenna arrays or sub-arrays as described in 8.2.3

8.2.4 Devices with multiple antennas or multiple transmitters

Additional considerations apply to devices with multiple uncorrelated antennas or multiple transmitters or sources that operate independently and can operate in different frequency ranges. Their exposure shall be combined and reported in terms of the total exposure ratio, which is defined in 7.5 of IEC/IEEE 63195-1:2021. If SAR evaluation is required for the computation of the total exposure ratio, computational or experimental SAR results may be applied. The procedures of IEC/IEEE 62704-1:2017 or IEC/IEEE 62704-4:2020 shall be followed for computational SAR evaluation, and the procedures of IEC 62209-1528:2020 [9] for SAR measurements.

8.3 Considerations on the evaluation surface and dimensions of the computational domain

For the computation of $psPD$, the evaluation surface need not be contained entirely in the computational domain. The field components on it are computed directly by the computational method or by expansion techniques applying the surface equivalence principle. The positioning of the evaluation surface with respect to the DUT shall be carried out according to 7.2.4 of IEC/IEEE 63195-1:2021. See 8.1 for details.

In the far-field of a DUT, the $psPD$ is likely to occur in the direction of the main beam. In the near-field, it may be located anywhere above the surface of the DUT. Depending on the field distribution, the dynamic range of the field pattern, and the dimensions of the computational domain, the absorbing boundary conditions can introduce significant uncertainties for the evaluation of the $psPD$; these uncertainties are considered in the computational uncertainty budget (9.2.3). The fields outside the computational domain that are determined by applying the surface equivalence principle are subject to the same sources of computational uncertainty.

If the evaluation surface is not entirely included in the computational domain and the electric field and magnetic field on it are evaluated using the surface equivalence principle, the computational domain shall be chosen such that the reactive field of the DUT is not cut off by the absorbing boundary conditions. The extension of the reactive field is not known beforehand. Hence, the dimensions of the computational domain shall be determined in a series of computations with increasing dimensions of the computational domain. The dimensions of the near-field may be identified by comparison of the ratio of the local electric field and magnetic field amplitudes to the free space wave impedance.

8.4 Averaging of power density on an evaluation surface

8.4.1 General

The $psPD$ is evaluated as the absolute maximum of the sPD , which is computed on an evaluation surface for an averaging area of a given size and shape. The evaluation surface is specified in 8.1. For the computation of the sPD , the power passing through the surface is computed by computational integration of the power density PD over a surface $\hat{A}$ within the averaging area A_{av} . The size of the averaging A_{av} is specified in the respective exposure guidelines [7], [8] as 1 cm² or 4 cm² depending on the operational frequency of the DUT. Depending on the shape of the evaluation surface, two different approaches are applied to construct the averaging area.

- a) If the evaluation surface is entirely planar, the averaging area has the shape of a square with the edge length $a_{av} = \sqrt{A_{av}}$. The square averaging area shall entirely be contained in the evaluation surface. See 8.4.2.1 for details. In this case, the area of $\hat{A}$ is identical to the averaging area A_{av} .
- b) If the evaluation surface is not entirely planar, the averaging area is constructed as the intersection of the evaluation surface with a sphere with a radius $r_{av} = \sqrt{A_{av}/\pi}$. The centre point of the sphere is a point on the evaluation surface, and the area $\hat{A}$ is the region of the evaluation surface that is contained in the sphere. The area $\hat{A}$ may deviate from A_{av} .

NOTE 1 Typically, the square shaped averaging area is applied on a surface that is established by a flat phantom. The intersection with a sphere is applied when averaging, e.g. over the inner shell of the SAM head.

NOTE 2 The averaging algorithm for planar evaluation surfaces using a square averaging in this document is specified to align with the definitions of the shape of the averaging area as defined in the exposure guidelines [7], [8]. While the guidelines foresee the application of a square averaging area on non-planar evaluation surfaces, it is important to note that a sphere is used for non-planar evaluation surfaces to construct the shape of the averaging area to keep the implementation of the algorithm simple. The specification of an averaging algorithm for non-planar evaluation surfaces based on a rotating cube is foreseen for the revision of this document. Such an algorithm would yield an averaging area that approximates a square shape on non-planar evaluation planes. A suggestion for a specification is given in Annex G.

The evaluation surface or parts of it may be contained in the computational domain. Electric and magnetic fields on the evaluation surface outside the computational domain shall be computed using the surface equivalence principle.

8.4.2 Construction of the averaging area on an evaluation surface

8.4.2.1 Planar evaluation surface

For the evaluation of the sPD on a planar evaluation surface, the averaging area shall be constructed as a square with the edge length $a_{av} = \sqrt{A_{av}}$ around each centre point. The centre points are the vertices of the triangulated evaluation surface, and the square shall be contained entirely in the evaluation surface.

NOTE IEC TR 63170:2018 [2] specifies the intersection with the sphere or circle.

The evaluation surface shall be triangulated. The edge lengths of the triangles shall not exceed d_T , which shall be 1 mm or $\lambda/10$ (whichever is less). The square shall be rotated around its centre point in steps not larger than 5° to find the orientation that maximizes the power that passes through the square. If any of the corner points of the square lies outside the evaluation surface for any of the rotation angles, no sPD shall be computed for the centre point of the square even if the square is entirely contained in the evaluation surface for one or more orientation angles.

The triangulation points may coincide with the nodes of a Cartesian mesh. As an alternative to the triangulation, the evaluation surface may be subdivided in rectangles with a maximum edge length d_T .

Example algorithms for the construction of the averaging area on a planar evaluation surface are given in Clause D.1. The implementation of the algorithm shall be verified according to the verification benchmarks for the power density averaging algorithm as specified in A.6.2.

8.4.2.2 Non-planar evaluation surface

For the evaluation of sPD on a non-planar evaluation surface, any triangulation algorithm may be used to triangulate the evaluation surface. The edge lengths of the triangles shall not exceed d_T , which shall be 1 mm or $\lambda/10$ (whichever is less). Averaging areas shall be constructed around each centre point on the evaluation surface with the help of a sphere of a fixed size and a radius $r_{av} = \sqrt{A_{av}/\pi}$. The centre points are the vertices of the triangulated evaluation surface.

The area of the cross section of the sphere that contains the centre point has the size A_{av} . The sPD shall then be evaluated by determining the area of the evaluation surface that is contained in the sphere (Figure 5). Only those triangles shall be considered for the averaging that are connected to the triangle that contains the centre point via other triangles that are located completely inside the sphere. Triangles are regarded as connected if they share a vertex.

NOTE Connecting all triangles of the averaging area to the triangle containing the centre point by triangles that are contained in the sphere prevents disjunct averaging areas, which can otherwise occur, e.g. in neighbouring fingers.

Example algorithms for the construction of the evaluation areas on a non-planar surface are given in Clause D.2. The implementation of the algorithm shall be verified according to the verification benchmarks for the power density averaging algorithm as specified in A.6.3.

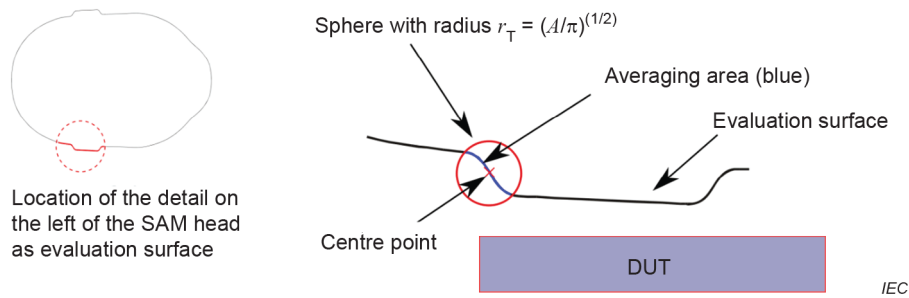


Figure 5 – Example of the construction of the averaging area within a sphere with fixed radius according to 8.4

8.5 Computation of sPD by integration of the Poynting vector

8.5.1 General

The sPD is evaluated at the location r as a function of the complex Poynting vector S . Depending on the dominant direction of incidence and polarization of the electromagnetic field or exposure in the near-field of the DUT, 8.5.2, 8.5.3, and 8.5.4 specify the expressions for the computation of the sPD for the different specifications of the PD . Weighting functions in the integrands of the expressions of 8.5.2, 8.5.3, and 8.5.4 avoid contributions from regions where the Poynting vector is oriented outward from the evaluation surface or due to computational inaccuracies for surfaces which are almost parallel to the direction of the Poynting vector, by scaling down the integrand at these regions to zero.

NOTE 1 The areas of the triangles (8.4.2) on which the integrand is scaled down or set to zero by a weighting function fully contribute to the averaging area.

NOTE 2 IEC TR 63170:2018 [2] does not consider the direction of the Poynting vector with respect to the orientation of the evaluation surface. This corresponds to setting the weighting functions of the expressions in 8.5.2 and 8.5.3 equal to 1.

NOTE 3 The expression used to compute the PD can depend on the applicable exposure guidelines or national regulations.

8.5.2 Surface-normal propagation-direction power density into the evaluation surface, sPD_{n+}

The surface-normal propagation-direction power density into the evaluation surface, sPD_{n+} , shall be computed according to Formula (4):

$$sPD(r_0) = \frac{1}{\hat{A}(r_0)} \int_{\hat{A}(r_0)} \Re\{S(r)\} \cdot n_A(r) \cdot \Theta[\Re\{S(r)\} \cdot n_A(r)] d\hat{A}(r) \quad (4)$$

where

- $\Re\{S(r)\}$ is the real part of the complex Poynting vector S at the location r ;
- $n_A(r)$ is the normal vector of the evaluation surface at the location r pointing into the evaluation surface, with $\|n_A(r)\| = 1$;
- $\Theta(x)$ is the Heaviside (unit step) function of x ;
- $\hat{A}(r_0)$ is the square or the intersection of the sphere and the evaluation surface that is directly connected to the location r , i.e. the sum of the areas of the triangles inside the sphere that are considered for the computation of the sPD at the location r ;
- r_0 is the location of the centre point.

NOTE 1 The surface normal propagating power density into the phantom as defined in IEC TR 63170:2018 [2] corresponds to sPD_{n+} with $\Theta(x) = 1$.

NOTE 2 Formula (4) corresponds to power density crossing a surface A , i.e. the energy per unit time and unit area crossing a surface of area A_{av} .

8.5.3 Total propagating power density into the evaluation surface, sPD_{tot+}

The total propagating power density into the evaluation surface, sPD_{tot+} , shall be computed according to Formula (5), along with Formula (6) and Formula (7).

$$sPD(r_0) = \frac{1}{\hat{A}(r_0)} \int_{A(r_0)} \left\| \Re\{S(r)\} \right\| \cdot \Xi \left\{ \cos^{-1} [n_R(r) \cdot n_A(r)] \right\} d\hat{A}(r) \quad (5)$$

where

$$n_R(r) = \Re\{S(r)\} / \left\| \Re\{S(r)\} \right\| \quad (6)$$

$$\Xi(\theta) = \begin{cases} 1, & 0 \leq \theta < 85^\circ \\ 1 - (\theta - 85^\circ)/5^\circ, & 85^\circ \leq \theta < 90^\circ \\ 0, & \theta \geq 90^\circ \end{cases} \quad (7)$$

$\left\| \Re\{S(r)\} \right\|$ is the magnitude of the real part of the complex Poynting vector S at the location r ; other terms are as specified in 8.5.2.

NOTE 1 The total propagating power density into the evaluation surface as defined in IEC TR 63170:2018 [2] corresponds to sPD_{tot+} with $\Xi(\theta) = 1$.

NOTE 2 Formula (5) corresponds to magnitude of the real part of the Poynting vector on a surface A , i.e. providing an overestimation of Formula (4).

8.5.4 Total power density directed into the phantom considering near-field exposure, sPD_{mod+}

The quantity sPD_{mod+} is based on the total power density and considers also the imaginary part of the Poynting vector to account for non-propagating energy transfer in the reactive near-field region. It shall be computed according to Formula (8).

$$sPD(r_0) = \frac{1}{\hat{A}(r_0)} \int_{A(r_0)} \left[\left(\left\| \Re\{S(r)\} \right\| \cdot \Xi \left\{ \cos^{-1} [n_R(r) \cdot n_A(r)] \right\} \right)^2 + \left(\left\| \Im\{S(r)\} \right\| \right)^2 \right]^{1/2} d\hat{A}(r) \quad (8)$$

where

$\left\| \Im\{S(r)\} \right\|$ is the magnitude of the imaginary part of the complex Poynting vector S at the location r ;

other terms are as specified in 8.5.2 and 8.5.3.

NOTE Formula (8) corresponds to magnitude of the Poynting vector (real and imaginary parts) on a surface A , i.e. an overestimation of Formula (4) and Formula (5).

8.6 Software

The software that implements power density averaging according to 8.4 shall make reference to this document, [7], [8], and if applicable, to [10]. In its graphical user interface or in its command line interface, the software shall provide the following options for the averaging.

- a) Construction of the averaging area based on a
 - "sq": rotating square for planar evaluation surfaces (8.4.2.1).
 - "circ": sphere for non-planar evaluation surfaces (8.4.2.2).
- b) Computation of the sPD based on the
 - sPD_{n+} ("area": "circ" or "sq"): surface normal propagating power density directed into the phantom averaged over "area" in units of cm^2 (e.g. 1 cm^2 or 4 cm^2) with the intersection of the sphere (circ) or cube (sq) (8.5.2).
 - sPD_{tot+} ("area": "circ" or "sq"): total propagating power density directed into the phantom averaged over "area" units of cm^2 (e.g. 1 cm^2 or 4 cm^2) with the intersection of the sphere (circ) or cube (sq) (8.5.3).
 - sPD_{mod+} ("area": "circ" or "sq"): averaged over "area" units of cm^2 (e.g. 1 cm^2 or 4 cm^2) with the intersection of the sphere (circ) or cube (sq) (8.5.4).

The options in the graphical user interface of the software shall be labelled according to the list above. Functions in the command line interface shall be documented with reference to the relevant subclauses of this document.

The software shall display a warning message if the selected dimensions of the averaging area A_{av} are not compliant with [7], [8] or this document considering the dimensions of 1 cm^2 or 4 cm^2 , the evaluation frequency and if planar averaging is applied on a non-planar surface or if the non-planar averaging is applied on a planar surface. Implementation examples are given in Annex D.

9 Uncertainty evaluation

9.1 General

The procedures described for the evaluation of the computational uncertainty are based on those of IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020 and were adapted to the particular requirements of this document considering both FDTD and FEM. They include the evaluation of the uncertainty contribution of the computational parameters (9.2), the uncertainty contribution of the computational representation of the DUT (9.3) and the uncertainty of the maximization of the $psPD$ (9.4)

The evaluation of the uncertainty contribution of the computational representation of the DUT due to the computational parameters specified in 9.2 is required a) for the validation of the computational model according to 7.5.3 and b) for the evaluation of the overall uncertainty of the $mpsPD$. Hence, the procedures of 9.2 apply to both the evaluation of the sPD and of the $mpsPD$.

9.2 Uncertainty of the sPD and of the $mpsPD$ due to the computational parameters

9.2.1 Uncertainty contributions due to the computational parameters

Table 1 specifies the uncertainty budget of the contributions of the computational parameters to the results of the validation setup or testing setup. The details on how to quantify the uncertainty components are described in 9.2.2, 9.2.3, 9.2.4, 9.2.5, 9.2.6, 9.2.7 and 9.2.8.

Table 1 – Budget of the uncertainty contributions of the computational algorithm for the validation setup or testing setup

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance %	Probability distribution	Divisor	c_i	Uncertainty %	v_i or v_{eff}
Mesh resolution	9.2.2		N	1	1		
ABC	9.2.3		N	1	1		
Power budget	9.2.4		N	1	1		
Model truncation	9.2.5						
Convergence	9.2.6		R	1,73	1		
DUT dielectrics	9.2.7		N	1	1		
Lossy conductors	9.2.8		R	1,73	1		
Combined standard uncertainty ($k = 1$)							
Columns c, g, and h shall be filled in based on the results of the DUT computations. NOTE 1 Column headings a to h are given for reference. NOTE 2 Abbreviations used in Table 1: N – normal probability distribution; R – rectangular probability distribution NOTE 3 The divisor is a function of the probability distribution (d) and degrees of freedom (v_i and v_{eff}) (h). NOTE 4 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of the <i>sPD</i> or <i>mpsPD</i>.							

9.2.2 Mesh resolution

9.2.2.1 FEM meshes

The mesh density has a major impact on the accuracy of the results; therefore, *sPD* and *mpsPD* results produced with a particular initial mesh *M* need to be compared with results produced with a denser mesh *M'*. Either of the following two strategies shall be applied depending on whether the FEM code used for the evaluation employs adaptive mesh refinement or not.

- If the applied FEM code does not employ adaptive mesh refinement, the number of mesh elements per wavelength used for the initial mesh *M* shall be increased by at least 50 % considering the respective wavelengths in the dielectrics.
- If the applied FEM code employs adaptive mesh refinement, additional adaptive passes shall be performed until the number of mesh elements has increased by at least 20 % for second or third lowest order and 50 % for lowest order.

In both cases, the *PD* shall be recorded in the region where the *sPD* or *mpsPD* maximum is expected. Both minimum and maximum edge lengths in this region and in the region around the antenna of the denser mesh *M'* shall be less than or equal to 50 % of the respective edge lengths of *M*. The location of the *sPD* or *mpsPD* maximum in the region of mesh *M'* shall not deviate by more than the minimum mesh edge length from the location of the electric field maximum within the respective region of mesh *M*. The maximum *sPD* or *mpsPD* deviation shall be reported in Table 1 as uncertainty with rectangular probability distribution.

9.2.2.2 FDTD meshes

The effect of the mesh resolution shall be determined by increasing the number of mesh cells by increasing their total number by a factor of two with respect to the original computation. The mesh refinement that leads to the increase of the number of cells shall be applied in the region of the *sPD* or *mpsPD* maximum. Both minimum and maximum edge lengths in this region and in the region around the antenna of the denser mesh M' shall be less than or equal to 50 % of the respective edge lengths of M . The location of the *sPD* or *mpsPD* maximum in the region of mesh M' shall not deviate by more than the minimum mesh edge length from the location of the electric field maximum within the respective region of mesh M .

The maximum deviation of the *sPD* or *mpsPD* shall be reported in Table 1 assuming normal probability distribution.

9.2.3 Absorbing boundary conditions

The impact of the absorbing boundaries conditions shall be determined by moving the boundaries outward by a $\lambda/4$ in all directions. The maximum deviation of the *sPD* or *mpsPD* shall be reported in Table 1 assuming rectangular probability distribution.

NOTE The location of the maximum electric or magnetic energy at the boundary can correspond to the main beam of a radiating structure or to its reactive field.

9.2.4 Power budget

The power fed into the computational domain shall be recorded at the sources (P_M or P_O). The sum of the power absorbed in the lossy dielectrics, lossy conductors and passive components in the computational domain and radiated into the ABCs shall be recorded and compared to P_M or P_O . The deviation shall be reported in Table 1 assuming normal probability distribution.

When simulating devices with multiple sources operating simultaneously, it is recommended to excite each port separately while loading the inactive ports with the reference impedance in order to compute the full *S*-matrix of the multiport system. As such, the *psPD* and the power budget for a given excitation vector can be computed by superimposing the fields for any excitation vector and load. For details refer to, for example, [10].

9.2.5 Model truncation

The impact of the model truncation on *sPD* or *mpsPD* shall be evaluated by appropriate comparison to the untruncated model. See step g) of 7.2.

9.2.6 Convergence

9.2.6.1 Frequency domain FEM solvers

For FEM meshes, the convergence uncertainty is already covered by the mesh resolution uncertainty (9.2.1). No additional uncertainty contribution shall be applied.

9.2.6.2 FDTD computations with harmonic excitation

The electric field vector components shall be recorded in the time domain in the region where the maximum *sPD* or *mpsPD* is located. The absolute value of the vector shall be computed at each time step. For a sufficiently converged computation, the deviation of the last three local maxima (of the time-domain signal) of the squared absolute values of the electric fields from their mean value shall not be larger than 2 %, and the maxima shall be found in the same voxel. If the computation cannot be run for a sufficient time to reach a deviation of less than 2 %, a rationale shall be given in the test report explaining why a relaxed tolerance can be used for the particular application under test to rule out incorrectly configured computations, i.e. to which extent the convergence contributes to the target quantity.

9.2.6.3 FDTD computations with broadband excitation

For broadband computations with evaluation of the *sPD* or *mpsPD* by Fourier transformation, a signal with a pulse shaped envelope is used for excitation. The electric field components shall be recorded in the time domain as described in 9.2.6.2. If the *sPD* or *mpsPD* is evaluated at several frequencies, frequency-dependent changes in location of the target quantity shall be considered. For the evaluation of the uncertainty, the discrete Fourier transform (DFT) of the time-domain signal shall be computed for increasing windowing lengths t_w starting at $t_0 = 0$ and ending at $t_w = 1,25 \times n \times T$. T is the period of the evaluation frequency and n is an integer number that shall be increased until t_w reaches the end of the computed time or until the convergence limit has been reached. The deviation of the last two squared absolute values of the DFT results at the evaluation frequency from their mean value shall not be larger than 2 % for a sufficiently converged computation. If the computation cannot be run for a sufficient amount of time to reach a deviation of less than 2 %, a rationale shall be given in the test report explaining why a relaxed tolerance is used for the particular application under test to rule out incorrectly configured computations.

9.2.6.4 Reporting the convergence uncertainty

The deviation shall be reported in Table 1 as uncertainty with rectangular probability distribution.

Since the location of the *sPD* or *mpsPD* is generally not known beforehand, it is recommended to select the relevant region large enough to avoid repeated computations. Testing computations with coarser meshes or simplified geometry can help to limit the computational expenses to identify the relevant regions for the recording of the signals.

9.2.7 Dielectric properties

The dielectric properties of the DUT model are usually affected by uncertainties according to their specification. The impact of these uncertainties on the *sPD* or *mpsPD* shall be evaluated by applying the minimum and maximum conductivity and permittivity (four different combinations). The minimum and maximum shall be chosen according to the uncertainty that is reported in the reference documentation of the dielectric properties, e.g. data sheet, publication. In order to avoid excessive numbers of computations for structures with a large number of different dielectrics, the changes in conductivity and permittivity may be limited to the region where most of the electromagnetic energy is confined or absorbed, or advanced statistical methods may be applied for the quantification of the uncertainty. In such cases, an appropriate rationale shall be given. The deviation shall be reported in Table 1 as uncertainty with normal probability distribution.

9.2.8 Lossy conductors

The finite conductivity of the conductors of the DUT shall be varied according to their specification. The impact of the specified uncertainties shall be evaluated by applying the minimum and maximum conductivity of all conductors of the DUT (two computations). The minimum and maximum shall be chosen according to the uncertainty that is reported in the reference documentation of the conductors, e.g. data sheet, publication. The deviation shall be reported in Table 1 as uncertainty with rectangular probability distribution.

9.3 Uncertainty contribution of the computational representation of the DUT model

The uncertainty contribution of the computational representation of the DUT model shall be determined by the experimental and computational evaluation of the distribution of the *PD* in a plane at the distance validation measurement in the near-field (7.5.2.2) with a cross section of the dimensions of the evaluation surface on a rectilinear mesh with steps no larger than $\lambda/4$ with at least 100 points. The uncertainty is evaluated according to Formula (9).

$$U_d[\%] = 100 \times \max_n \left\{ \frac{|v_{\text{meas},n}^2 - v_{\text{sim},n}^2|}{\max \left(\max_n |v_{\text{meas},n}^2|, \max_n |v_{\text{sim},n}^2| \right)} \right\} \quad (9)$$

where

$v_{\text{meas},n}^2$ is the experimentally determined *PD* at position *n* or its accurate reference solution;

$v_{\text{sim},n}^2$ is the computationally determined *PD* at position *n*.

The mesh step mentioned in 9.3 refers to the measurement mesh. For the computational evaluation, a finer mesh is generally required.

The reference documentation of the applied instrumentation and/or appropriate measurement standards describing the specific application of this general approach should provide sufficient details to help facilitate correctness of the reference configuration setup. The uncertainties shall be reported in Table 2.

Table 2 – Budget of the uncertainty of the developed model of the DUT

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance %	Probability distribution	Divisor	c_i	Uncertainty %	v_i or v_{eff}
DUT model (field distribution in the near-field)	9.3		N	1	1		
Measurement equipment and procedure	According to manufacturer specification and/or applied methodology including the evaluation of the conducted or radiated power measurement (7.4.3)		N	1	1		
Combined standard uncertainty ($k = 1$)							
Columns c, g and h shall be filled in based on the results of the DUT computations.							
NOTE 1 Column headings a to h are given for reference.							
NOTE 2 Abbreviation used in Table 2:							
N – normal probability distribution							
NOTE 3 The divisor is a function of the probability distribution (d) and degrees of freedom (v_i and v_{eff}) (h).							
NOTE 4 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of the <i>sPD</i> or <i>mpsPD</i> .							

9.4 Uncertainty of the maximum exposure evaluation

For codebooks that are relatively small, such that the exhaustive search method shall be used, the uncertainty of the maximum exposure evaluation is zero.

For codebooks that are too large for the exhaustive search method, use the hybrid optimization methods described in Annex C. The optimization shall be repeated ten times with random initial conditions. Each time, the *mpsPD* shall be recorded. The uncertainty from the evaluation of the field maximization shall then be then computed using Formula (10).

$$U_m [\%] = 100 \times \left\{ \frac{\max_{i=[1,10]} \{mpsPD_i\} - \min_{i=[1,10]} \{mpsPD_i\}}{\max_{i=[1,10]} \{mpsPD_i\}} \right\} \quad (10)$$

where $mpsPD_i$ is the maximum *psPD* found by the optimizer at the *i*-th run.

9.5 Uncertainty budget

The total uncertainty budget shall be computed from the contributions of Table 1 and Table 2 and shall be summed up as shown in Table 3. The minimum achievable uncertainty depends on the level of detail to which a particular exposure situation can be computed. Relatively high uncertainties can occur, for example, from the dielectric properties or conductor losses of the DUT.

NOTE Application examples available at the time of the development of this document indicate that the expected levels of uncertainties are similar to those indicated in the NOTE to 7.4 of IEC/IEEE 62704-1:2017, i.e. in the order of magnitude of 20 % ($k = 2$). The level of the acceptable uncertainty depends on the application. Revisions of this document will provide more robust values of the acceptable uncertainty based on application cases and published data.

Table 3 – Computational uncertainty budget

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance %	Probability distribution	Divisor	c_i	Uncertainty %	v_i or v_{eff}
Test setup with respect to computation parameters	9.2		N	1	1		
Computational model of the test setup	9.3		N	1	1		
Field maximization	Annex C		N	1	1		
Combined standard uncertainty ($k = 1$)							
Expanded uncertainty ($k = 2$)							
Columns c, g and h shall be filled in based on the results of Table 1 and Table 2.							
NOTE 1 Column headings a to h are given for reference.							
NOTE 2 Abbreviation used in Table 3:							
N – normal probability distribution							
NOTE 3 The divisor is a function of the probability distribution (d) and degrees of freedom (v_i and v_{eff}) (h).							
NOTE 4 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of the <i>mpsPD</i> .							

10 Reporting

The test report shall contain the description of all steps that show the development and experimental validation of the DUT model, the tests that were performed and their results with respect to the applicable exposure standards as well as the uncertainty budget. These steps shall be described such that the development and computational evaluation of the DUT model can be reproduced independently. In detail, the testing report shall contain the following sections.

a) General:

- 1) identification of the test laboratory;
- 2) conformity requirements, e.g. test standards, exposure guidelines;
- 3) applicable exposure limits, e.g. ICNIRP, IEEE/ICES [7], [8];
- 4) specification of the evaluation plane and the sPD (see 8.3, 8.4, 8.5, 8.6) formula(s) applied for the evaluation of the $mpsPD$;
- 5) identification of the software used for the testing, including version number, and statement of conformity with this document;
- 6) identification of the algorithm for computation of the $mpsPD$.

b) Description of the DUT:

- 1) identification of the DUT including hardware and software revision numbers, serial number;
- 2) description of the form factor of the DUT and a brief description of its intended function;
- 3) description of the operating modes of the DUT, such as frequency bands, power level, beam shaping options, codebook (if applicable);
- 4) description of the technical documentation provided for the development of the DUT model, such as CAD, data, circuit diagrams, data sheets.

c) Development of the DUT model:

- 1) overview of parts of the DUT that are included and excluded from the model, and rationale for the excluded parts;
- 2) description of the modelling of the sources, impedance matching, the RF signal paths and the antenna;
- 3) list of the applied dielectric material properties with references or a rationale for their values if no appropriate reference is available;
- 4) computation settings, such as mesh resolution, convergence criteria, dimensions of the computational domain, boundary conditions.

d) Validation of the DUT model:

- 1) description of the tests that were performed and rationale for choosing them;
- 2) measurement instrumentation;
- 3) measurement setup and protocol;
- 4) tabular and graphical comparison of measured and computed results including statement on applicability of the DUT model for the evaluation of the sPD ;
- 5) power reference plane chosen for the experimental quantification of P_R of the DUT, rationale for the choice and assumptions required for the computation of P_R ;
- 6) description and rationale for reduced number of validation tests for similar DUTs according to 7.5.4;
- 7) experimental and computational uncertainty budgets for the validation of the DUT model.

e) Performed tests and results:

- 1) description of the performed testing (positions, evaluation surfaces, etc.) according to 8.2;
- 2) applied method to evaluate the *mpsPD* (field maximization technique, optimization, codebook, etc.);
- 3) applied power normalization of computed results to DUT output;
- 4) list of all frequency bands and beam directions tested;
- 5) *mpsPD* over the testing positions, bands, operating modes, and device configurations including
 - i) total radiated power P_R (computational evaluation) of the DUT during the measurement (experimental evaluation),
 - ii) excitation vector,
 - iii) location and shape of the averaging area of the *mpsPD* by highlighting it on the evaluation surface in the graphical user interface of the evaluation software, and
 - iv) applied averaging algorithm according to 8.6.

f) Computational uncertainty budget of the overall evaluation of the *mpsPD*.

Annex A (normative)

Code verification

A.1 General

Software applied for the computation of the $psPD$ for power density evaluation of wireless devices shall be verified according to IEC/IEEE 62704-1:2017 (FDTD) or IEC/IEEE 62704-4:2020 (FEM). For the computation of the $psPD$ according to this document, additional evaluations shall be carried out to verify the correct implementation of the interpolation and superposition algorithms (Clause A.2 and Clause A.3), of metallic losses (Clause A.4) and anisotropic dielectrics (Clause A.5). These are required for the efficient computational evaluation of phased array systems in the frequency range of the scope of this document. In addition, the implementation of the algorithm for the computation of the $psPD$ according to Clause 7 shall be verified (Clause A.6). These benchmarks are specified such that they can be applied both on FDTD- and FEM-based software.

A.2 Interpolation and superposition of vector field components

The correct implementation of interpolation and superposition of vector field components shall be verified by evaluating the fields from three $\lambda/2$ -dipoles, D_1 , D_2 , and D_3 , operating simultaneously at a frequency of 24 GHz with different amplitudes and phase offsets. The dipoles shall have lengths of 6,2 mm. The axis of the first dipole shall be aligned with the z -axis of the coordinate system, the axis of the second dipole shall be aligned with the x -axis of the coordinate system centred with its feed-point on the origin, and the axis of the third dipole shall be aligned with the y -axis of the coordinate system. The feed-points shall be placed in the centres of the dipoles. They shall be modelled as hard-sources or voltage sources with a finite inner resistance. The distances between centres of the feed-points shall be 7,0 mm. The configuration is shown in Figure A.1. In the FDTD computations, the x -axis intersects the feed-points in the centres of the dipoles D_1 and D_3 . To avoid this intersection, the feed-points may be modelled by two subsequent sources with equal signals. The feed-point of the dipole D_2 may be modelled by two subsequent sources, as well.

NOTE Inhomogeneous meshing (varying mesh step size) can be necessary for the discretization of this antenna configuration.

The dipoles shall be modelled as perfectly conducting filaments: the electric fields on their axis shall be zero, such that their diameter can be assumed to be significantly smaller than the length of the mesh edges in their cross sections. Alternatively, a diameter of 0,05 mm can be applied. The lengths of the mesh edges or vertices can be chosen by the software or the user.

The dipoles shall be excited with different source and amplitude and phase configurations given in Table A.1. The three dipoles shall be excited consecutively. The electric and magnetic fields shall be superimposed using the built-in post-processing functions of the software under test.

The x -, y - and z -vector components of the electric and magnetic fields shall be evaluated on two cubical surfaces with edge lengths of 10,0 mm and 16,0 mm centred about the origin. On the surfaces of the cube, evaluation points are specified on a rectilinear lattice with a spacing of 0,5 mm. All electric and magnetic vector field components of the fields computed with the software under test shall be compared to reference results on the six rectilinear lattices of the cube. The reference results are provided as supplemental files; see Annex I. The reference results are based on computation results obtained using the method of moments [11] codes that have been validated according to IEC/IEEE 62704-1:2017 or IEC/IEEE 62704-4:2020. The maximum deviation of the electric field and magnetic field amplitudes that are greater than or equal to 10 % of the maximum of the reference results shall be evaluated and reported in Table A.1. The maximum permissible deviation from the reference results is 10,0 %.

Dimensions in millimetres

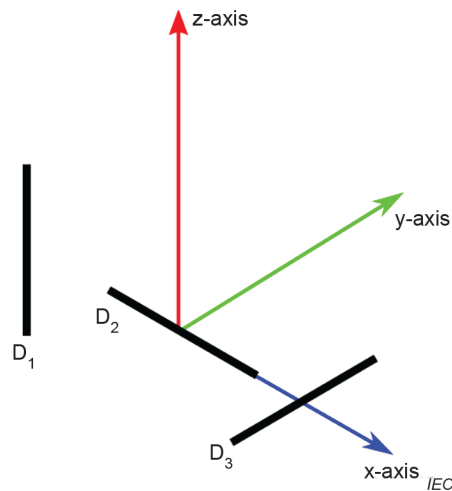


Figure A.1 – Configuration of three $\lambda/2$ dipoles, D_1 , D_2 , and D_3 , for the evaluation of the interpolation and superposition of the electric field and magnetic field components

Table A.1 – Interpolation and superposition of vector field components; maximum permissible deviation from the reference results is 10 %

Amplitudes and phases	Maximum deviation from reference on 10 mm cube		Maximum deviation from reference on 16 mm cube	
	electric field amplitude	magnetic field amplitude	electric field amplitude	magnetic field amplitude
Configuration 1 D_1 : $A = 1 \text{ V}$, $\varphi = 0^\circ$ D_2 : $A = 0,5 \text{ V}$, $\varphi = 90^\circ$ D_3 : $A = 2 \text{ V}$, $\varphi = 180^\circ$				
Configuration 2 D_1 : $A = 2 \text{ V}$, $\varphi = 0^\circ$ D_2 : $A = 2 \text{ V}$, $\varphi = 90^\circ$ D_3 : $A = 2 \text{ V}$, $\varphi = 0^\circ$				
Configuration 3 D_1 : $A = 1 \text{ V}$, $\varphi = 180^\circ$ D_2 : $A = 0,5 \text{ V}$, $\varphi = 90^\circ$ D_3 : $A = 2 \text{ V}$, $\varphi = 180^\circ$				

A.3 Computation of the far-field pattern and the radiated power

The far-field pattern and the radiated power P_R shall be computed for all dipole configurations specified in Table A.1 for consecutive and simultaneous excitation. For consecutive excitation, the fields shall be superimposed using the built-in functions of the software under test before computing P_R . The far-field pattern shall be computed in units of the electrical fields over the entire solid angle in steps of 10° for φ and θ over the entire solid angle starting at 0° for both φ and θ . Reference results are provided as supplemental files; see Annex I. The reference results are based on the average of computation results obtained using the method of moments. The maximum deviation of the electric field amplitudes that are greater than or equal to 10 % of the maximum of the reference results shall be evaluated and reported in Table A.2. The maximum permissible deviation from the reference results for the field amplitudes and for the total radiated power is 10,0 %.

Table A.2 – Computation of P_R ; maximum permissible deviation from the reference results is 10 % for the radiated power and for the electric field amplitude of the far-field pattern

Excitation	Amplitudes and phases	Computed power in watts	Reference power in watts	Maximum deviation of the electric field amplitude of the far-field pattern from reference
consecutive	D_1 : $A = 1 \text{ V}$, $\varphi = 0^\circ$		0,023 0	
	D_2 : $A = 0,5 \text{ V}$, $\varphi = 90^\circ$			
	D_3 : $A = 2 \text{ V}$, $\varphi = 180^\circ$			
	D_1 : $A = 2 \text{ V/m}$, $\varphi = 0^\circ$		0,052 7	
	D_2 : $A = 2 \text{ V/m}$, $\varphi = 90^\circ$			
	D_3 : $A = 2 \text{ V/m}$, $\varphi = 0^\circ$			
	D_1 : $A = 1 \text{ V/m}$, $\varphi = 180^\circ$		0,023 0	
	D_2 : $A = 0,5 \text{ V/m}$, $\varphi = 90^\circ$			
	D_3 : $A = 2 \text{ V/m}$, $\varphi = 180^\circ$			

A.4 Implementation of lossy conductors

The implementation of metallic conductors with finite conductivity shall be evaluated by modelling the decay of the propagating amplitude of the TE_{10} mode in a rectangular waveguide in terms of the complex propagation constant k_z . The evaluation of k_z follows the procedures specified in IEC/IEEE 62704-1:2017 and IEC/IEEE 62704-4:2020.

The complex propagation constant shall be evaluated in the computational model of an R320 waveguide with the inner cross section of $7,112 \text{ mm} \times 3,556 \text{ mm}$ over a frequency range from 25 GHz to 40 GHz. For the FDTD method, a broadband signal shall be used, and the attenuation constant $\text{Im}\{k_z\} = \alpha$ shall be evaluated as a function of the frequency. For FEM, discrete frequencies with a step size of 250 MHz shall be evaluated. All directions and dimensions correspond to the coordinate system as specified in Figure A.2. The excitation is placed perpendicular to the orientation of the waveguide. The distance from the source to the fields to be recorded shall be 1,778 mm. The length of the waveguide should be chosen such that spurious fields that can be caused by the truncation of the computational domain do not reach the region where the fields are recorded.

The walls of the waveguide shall be modelled as conductors with conductivities σ of 10^5 S/m, 10^6 S/m, and 10^7 S/m. The waveguide shall be filled with lossless dielectric materials with relative permittivities ϵ_r of 1 and 2. For each configuration, the waveguide shall be meshed with a fine and a coarse homogeneous or inhomogeneous mesh with at least a minimum mesh step according to Table A.3.

The E_y components at the source location (Figure A.3) shall be excited with the analytical solution of the TE₁₀ mode. The mode can be excited by setting the E_y components at the source location (Figure A.3) to the values computed from Formula (A.1):

$$E_y = E_0 \sin \frac{x\pi}{w} \quad (\text{A.1})$$

where

E_0 is a specifiable amplitude of the electric field vector;

x is the location of the x -component of the electric field vector;

w is the width of the waveguide (7,112 mm).

Alternative methods for the field excitation may be used, such as particular solvers to determine the propagating modes in the waveguide or preconfigured sources if the software provides them. In any case, it shall be asserted that only the fundamental propagating mode exists at the location where the fields are recorded (Figure A.3) because the presence of higher order modes or spurious modes hinders the evaluation of the propagation constant. The E_y component shall be recorded at the locations specified in Figure A.3. The complex propagation constant k_z can be computed from the field components recorded at the locations in Figure A.3 using Formula (A.2)

$$\alpha = \text{Im} \left[-\frac{j}{\Delta s} \ln \frac{E_{10} + E_{12} - \sqrt{-4E_{11}^2 + (E_{10} + E_{12})^2}}{2E_{11}} \right] \quad (\text{A.2})$$

where Δs is the distance between the locations of the recorded components (1,778 mm).

For FDTD, all results shall be evaluated and reported for the waveguide axis oriented along all three axes of the coordinate system, for two different orientations around the waveguide axis (rotate waveguide by 90°). α shall be evaluated for propagation along positive axis direction, only.

For each waveguide configuration in Table A.4, the maximum deviation of the attenuation constant α from its reference value shall be evaluated as a function of the frequency. Reference values have been derived according to Formula (A.3):

$$\alpha = 8,686 \frac{1}{b\eta} \sqrt{\frac{\omega\mu_0}{2\sigma}} \frac{\left[1 + \frac{2b}{a} \left(\frac{f_c}{f} \right)^2 \right]}{\sqrt{1 - \left(\frac{f_c}{f} \right)^2}} \quad [\text{dB/m}] \quad (\text{A.3})$$

where

- ω is the angular frequency;
- μ_0 is the free space permeability;
- σ is the conductivity of the waveguide walls;
- a is the waveguide width (also referred to as w);
- b is the waveguide height;
- η is the wave impedance of the dielectric in the waveguide;
- f is the frequency;
- f_c is the cutoff frequency of the waveguide.

The constant 8,686 converts the units of the attenuation coefficient computation results from Np to dB. Further details can be found in [12]. Reference solutions for Table A.4 are given in a separate file (Annex I). The deviations of α from its reference results shall be less than or equal to the tolerances given in Table A.4.

Dimensions in millimetres

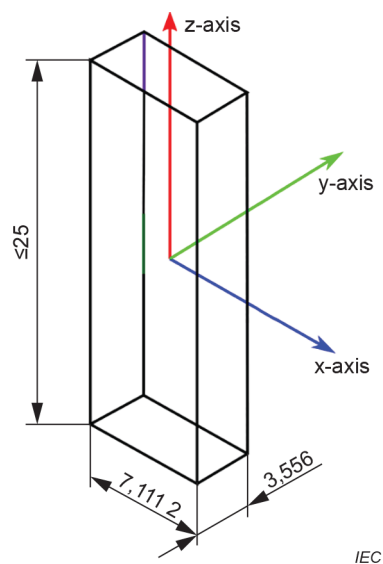


Figure A.2 – R320 waveguide