IEC TR 63377

Edition 1.0 2022-11

TECHNICAL REPORT

colour inside

Procedures for the assessment of human exposure to electromagnetic fields from radiative wireless power transfer systems – Measurement and computational methods (frequency range of 30 MHz to 300 GHz)

IEC TR 63377:2022-11(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 17.220.20, 33.050.10

ISBN 978-2-8322-5945-0

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PROCEDURES FOR THE ASSESSMENT OF HUMAN EXPOSURE TO ELECTROMAGNETIC FIELDS FROM RADIATIVE WIRELESS POWER TRANSFER SYSTEMS – MEASUREMENT AND COMPUTATIONAL METHODS (FREQUENCY RANGE OF 30 MHz TO 300 GHz)

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IEC TR 63377 has been prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
106/568/DTR	106/578/RVDTR

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 Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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INTRODUCTION

IEC TC 106 is tasked with preparing International Standards on measurement and simulation methods used to assess human exposure to electric fields, magnetic fields, and electromagnetic fields. Wireless power transfer (WPT) systems operating at 30 MHz to 300 GHz utilize electric fields, magnetic fields, or electromagnetic fields to provide power to equipment nearby or at distances up to several metres or more. Users or bystanders in close proximity to both the transmitting equipment and receiving equipment or in between them could be exposed to these fields. Assessment methods are needed to demonstrate compliance with applicable human exposure limits. A working group (WG9) was established by IEC TC 106 to address assessment methods of human exposure to WPT equipment.

This document consists of an overview of radiative WPT, exposure assessment methods, procedures, and case studies, to help in the development of international standards for WPT exposure assessment. This document addresses the frequency range of 30 MHz to 300 GHz. For lower frequencies, WPT equipment operating below 10 MHz is covered by IEC TR 62905:2018, and below 30 MHz is covered by IEC PAS 63184:2021, with an associated subsequent International Standard currently under consideration by IEC TC 106. The methods and procedures described in this document are based on the techniques of other exposure standards covering the same frequency range. Other methods are referenced when deviations from these assessment methods are needed.

PROCEDURES FOR THE ASSESSMENT OF HUMAN EXPOSURE TO ELECTROMAGNETIC FIELDS FROM RADIATIVE WIRELESS POWER TRANSFER SYSTEMS – MEASUREMENT AND COMPUTATIONAL METHODS (FREQUENCY RANGE OF 30 MHz TO 300 GHz)

1 Scope

This Technical Report describes assessment methods to evaluate the compliance of radiative wireless power transfer (WPT) systems operating in the frequency range from 30 MHz to 300 GHz with electromagnetic guidelines on human exposure (electromagnetic field strength, specific absorption rate (SAR), and power density). This document includes but is not limited to systems that focus the electromagnetic energy emitted by the transmitter to regions surrounding the receiver, for example, by narrow beam-forming systems, wide-beam systems and spatially closed systems. Implementations without transmitter, for example, applications that harvest energy from the environment, are not included in the scope of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC 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

3.1
basic restriction
BR
human exposure limits for compliance with time-varying electric, magnetic, and electromagnetic fields evaluated inside the body that are based on established adverse health effects

Note 1 to entry: Within the scope of this document, the physical quantity used as a basic restriction is the specific absorption rate (SAR) or absorbed (epithelial) power density.

3.2
equipment under test
EUT
equipment that is tested according to the procedures described in this document

3.3
plane-wave equivalent power density
electromagnetic wave, magnitude of the power density of a plane wave having the same ratio of electric (E) field strength to magnetic (H) field strength

Note 1 to entry: The SI unit of plane-wave equivalent power density is watt per square metre (W/m^2).

3.4
exposure
<for a person> situation that occurs wherever a person is subjected to electric, magnetic, or electromagnetic fields

3.5
far-field region
<of an antenna> region of the electromagnetic field of an antenna wherein the predominant components of the field are those which represent a propagation of energy and wherein the angular field distribution is essentially independent of the distance from the antenna

[SOURCE: IEC 60050-712:1992 [1], 712-02-02, modified – Hyphen added to the term, notes to entry omitted.]

3.6
incident field
field that would exist in the absence of a person over a volume where a person could be located

Note 1 to entry: In some documents, the incident field is called an unperturbed field or environmental field.

3.7
reactive near-field region
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 the electric field and magnetic field components are 90° out of phase

[SOURCE: IEC/IEEE 63195-1:2022 [2], 3.2.10, modified – The word "region" has been added to the term.]

3.8
peak spatial-average SAR
psSAR
maximum SAR averaged within a local region based on a specific averaging mass, e.g. any 1 g or 10 g of tissue in the shape of a cube

[SOURCE: IEC/IEEE 62209-1528:2020 [3], 3.37, modified – The note to entry has been omitted.]

3.9
phantom
physical model with an equivalent human anatomy and comprised of a tissue-equivalent medium with dielectric properties specified in IEC/IEEE 62209-1528:2020

[SOURCE IEC/IEEE 62209-1528 [3], 3.39, modified – The wording "in this document" is replaced with "IEC/IEEE 62209-1528:2020".]

3.10
radiative wireless power transfer system
radiative WPT system
system that transfers power by radiation of electromagnetic energy from a transmitter to a receiver in the frequency range from 30 MHz to 300 GHz

3.11
reference level
RL
level of field strength or power density derived from the basic restrictions using conservative assumptions about exposure

Note 1 to entry: If the reference levels are met, then the basic restrictions will be complied with, but if the reference levels are exceeded, that does not necessarily mean that the basic restrictions will not be met.

[SOURCE IEC 62311:2019 [4], 3.1.22, modified – Abbreviated term "RL" added.]

3.12
specific absorption rate
SAR
measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency electromagnetic field

Note 1 to entry: The SAR in the tissue-equivalent medium can be determined by the rate of temperature increase or by E-field measurements, according to the following formula:

$$SAR = \frac{\sigma E^2}{\rho} = c_\mathrm{h} \left. \frac{\partial T}{\partial t} \right|_{t=0}$$

where

SAR is the specific absorption rate in W/kg;

E is the RMS value of the electric field strength in the tissue-equivalent medium in V/m;

σ is the electrical conductivity of the tissue-equivalent medium in S/m;

ρ is the mass density of the tissue-equivalent medium in kg/m^3;

c_h is the specific heat capacity of the tissue-equivalent medium in J/(kg K);

$\left. \frac{\partial T}{\partial t} \right|_{t=0}$ is the initial time derivative of temperature in the tissue-equivalent medium in K/s.

[SOURCE IEC/IEEE 62209-1528:2020 [3], 3.5.1, modified – The two formulae now appear on one line and units have been formatted as symbols rather than as written words.]

3.13
beamwidth
<of an antenna> in a specified plane containing the direction of maximum radiation or the axis of symmetry of a beam or a radiation lobe, angle between two directions (corresponding, for example, to a given fraction of the maximum radiation or to the first minimums) on both sides of this direction or axis

Note 1 to entry: The most generally used fraction is half-power beamwidth.

[SOURCE IEC 60050-712:2021 [1], 712-01-33, modified – Note 2 to entry omitted.]

3.14
whole-body SAR
wbSAR
SAR averaged over the whole body

3.15
epithelial power density
power flow through the epithelium per unit area directly under the body surface

[SOURCE IEEE Std C95.1^{TM}-2019 [5], 3.1, modified – Note 1 and Note 2 omitted.]

4 Symbols and abbreviated terms

4.1 Physical quantities

The internationally accepted SI units are used throughout this document.

Symbol	Quantity	Unit	Dimensions
c_h	Specific heat capacity	joule per kilogram per kelvin	J/(kg K)
E	Electric field strength	volt per metre, RMS	V/m
f	Frequency	hertz	Hz
H	Magnetic field strength	ampere per metre, RMS	A/m
J	Current density	ampere per square metre	A/m^2
P	Average (temporal) absorbed power	watt	W
S	Power density	watt per square metre	W/m^2
T	Temperature	kelvin	K
ε	Permittivity	farad per metre	F/m
λ	Wavelength	metre	m
σ	Electric conductivity	siemens per metre	S/m
μ	Permeability	Henrys per metre	H/m

NOTE In this document temperature is quantified in degrees Celsius, as determined by: T (°C) = T (K) − 273,15.

4.2 Constants

Symbol	Physical constant	Magnitude
η_0	Intrinsic impedance of free space	120π Ω or 377 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

4.3 Abbreviated terms

RF radio frequency
RMS root mean square
RSS root sum square
CW continuous wave
WPT wireless power transfer
DRL dosimetric reference limit
E-field electric field strength
ERL exposure reference level
EUT equipment under test
H-field magnetic field strength
ICNIRP International Commission on Non-Ionizing Radiation Protection
IC integrated circuit
PD power density
TE transverse electric
TM transverse magnetic
TEM transverse electromagnetic

5 Description of radiative wireless power transfer systems

5.1 General

Radiative WPT represents a solution to remotely charge low-power devices (e.g. sensors, RF identification tags, mobile and wearable devices [6][1], [7]) and high power applications [8] over large distances.

Radiative WPT allows for greater distances to be covered than non-radiative WPT and does not require mutual coupling between the transmitter and receiver. However, the longer distances generally result in lower beam efficiency at the receiving end.

In a radiative WPT system, highly directional antennas are mostly used to transmit electromagnetic power and the system efficiency benefits from a highly directive receiver antenna when operated outside the near-field zone. The main theory of WPT via RF beam is based on the Friis transmission formula:

$$\frac{P_\mathrm{r}}{P_\mathrm{t}} = G_\mathrm{r} G_\mathrm{t} \left(\frac{\lambda}{4\pi R} \right)^2 \tag{1}$$

where

P_r and P_t are the receive power and transmit power, respectively,

G_t and G_r are the gains of the transmit antenna and receive antenna,

λ is the wavelength representing the effective aperture area of the receive antenna, and

R is the distance between the two antennas.

A rectenna [9] is normally used to convert the received electromagnetic power into usable direct current (DC) power.

5.2 Radiative WPT systems technology and applications

5.2.1 General

Radiative WPT systems can be classified according to the following list of technologies, and as shown in Figure 1:

a) wide beamwidth transmission to multiple receivers at short range;

b) space diversity WPT to a single receiver (using multi-path propagation);

c) narrow beamwidth transmission to a single receiver at either short or long range [10].

NOTE Narrow beamwidth and space diversity systems apply directed beams in order to maximize efficiency of the transmitted power towards a single receiver. Directive antennas can be used on the transmitter and/or the receiver side. Wide beamwidth systems transmit power to multiple receivers and might not necessarily direct the transmitted power towards them. Because of the large number of possible configurations of transmitter and receiver antennas, a more detailed specification of wide and narrow beamwidth systems might be too restrictive for present and upcoming technologies.

Each of the technologies in the preceding list can be used in different WPT applications (Table 1). A detailed description of these WPT applications can be found in [10].

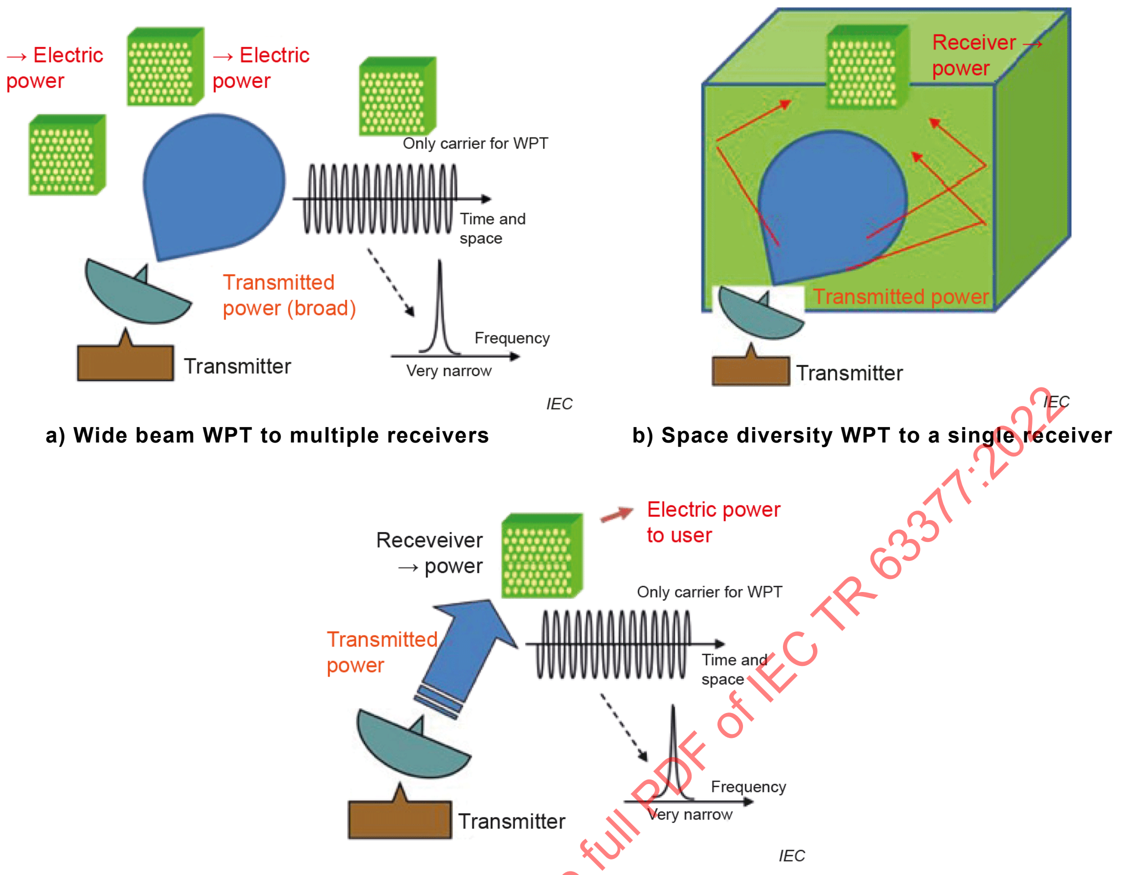
Energy harvesting is another wireless power technology that converts environmental electromagnetic energy into electric power. Due to its typically low conversion efficiency and low collection of power, it can be adequate to run or recharge small wireless micropower devices

[1] Numbers in square brackets refer to the Bibliography.

such as remote sensors. It does not include a transmitter for the RF power and therefore does not fall under the scope of this document.

Table 1 – Representative characteristics of potential radiative WPT applications

WPT application	Frequency band	Condition	Distance	Tx antenna gain	Transmit power
Wirelessly powered sensor network	915 MHz band, 2,45 GHz band, 5,8 GHz band	Indoor, Outdoor	Several metres to dozens of metres	6 dBi (Typically 915 MHz band), 25 dBi (Typically 2,45 GHz and 5,8 GHz bands)	< 50 W
Wireless charging of mobile devices	2,45 GHz band, 915 MHz band	Indoor	Several metres to dozens of metres	25 dBi (Typically 2,45 GHz band)	< 50 W
WPT to moving/flying target	2,45 GHz band, 5,8 GHz band	Indoor, Outdoor	several metres to 20 km	10 dBi to 30 dBi (Typically 5,8 GHz band)	50 W to 1 MW
Point-to-point WPT	2,45 GHz band, 5,8 GHz band	Outdoor	1 m to 20 km		100 W to 1 MW
Wireless charging for electric vehicle	2,45 GHz band, 5,8 GHz band	Outdoor	0,1 m to 1 m		100 kW to 500 kW
Solar power satellite	5,8 GHz band	Space to ground	36 000 km		1,3 GW
IoT devices, automation, point-to-point, etc.	24 GHz band, 61 GHz band, 122 GHz band, 244 GHz band	Indoor, Outdoor	1 m to 1 000 m		100 W



a) Wide beam WPT to multiple receivers

b) Space diversity WPT to a single receiver

c) Narrow beam WPT to a single receiver

[SOURCE: Figure 3.1 of ITU-R SM.2392-0 [10]][2]

Figure 1 – WPT system classification via radio-frequency beam technologies

Omnidirectional radiative WPT uses a wide beam transmission to transfer power to single or multiple users (receivers) over a distance. Figure 2 illustrates the beam pattern. The transmitter transmits electromagnetic waves with high energy and the receiver(s), using a rectenna, convert these waves into power. Due to low efficiency of these systems, only a small fraction of the radiated power is received by the receiver(s).

2 Reproduced from ITU-R SM.2392-0, with the permission of ITU-R.

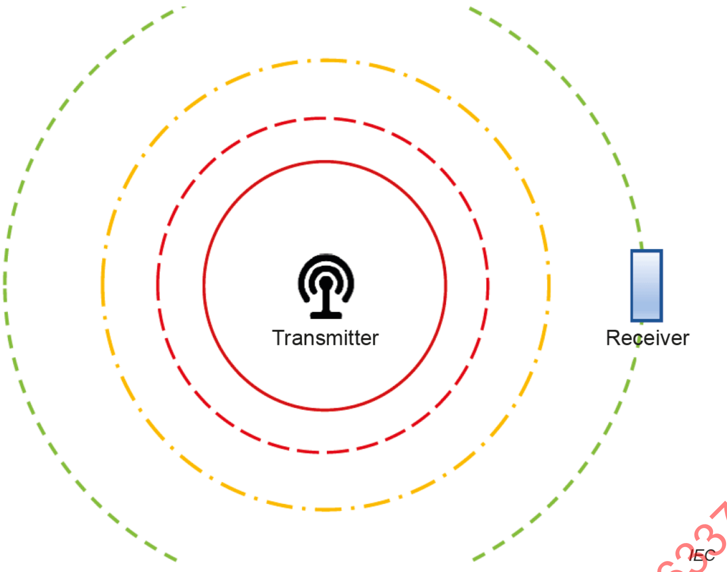


Figure 2 – Beam pattern diagram of omnidirectional radiative WPT

5.2.2 Operating principle of space diversity WPT

The basic principle of the space diversity WPT system is shown in b) of Figure 1 and the beam pattern is illustrated in Figure 3. The main application of such systems is related to the indoor environment where strong multi-path reflection from the walls is utilized to deliver the RF power to the receiver. In a typical space diversity WPT system, a receiver IC chip, built into a receiver device, sends out a low-level beacon signal that seeks the transmitter. Once received, the transmitter sends the RF power back through all the multi-paths from where the beacon signal was received. Such a multi-path functionality allows it to continuously send power from the transmitter so that the power is then delivered mostly to the receiving antenna and less elsewhere. This beacon process repeats, for example up to 100 times per second, which makes it possible to send the power over a distance and while the receiving device is in motion, even if people or objects are in the way. The bandwidth of the transmitted signals is supposed to be sufficiently small not to affect the pathway of the transmitted energy. Hence, the signals can be regarded as CW.

Nevertheless, in this application scenario, RF power could be delivered to other objects within the reflected beam, including human tissue. Considering this, the assertion of human safety operation is confirmed and demonstrated by the assessment results.

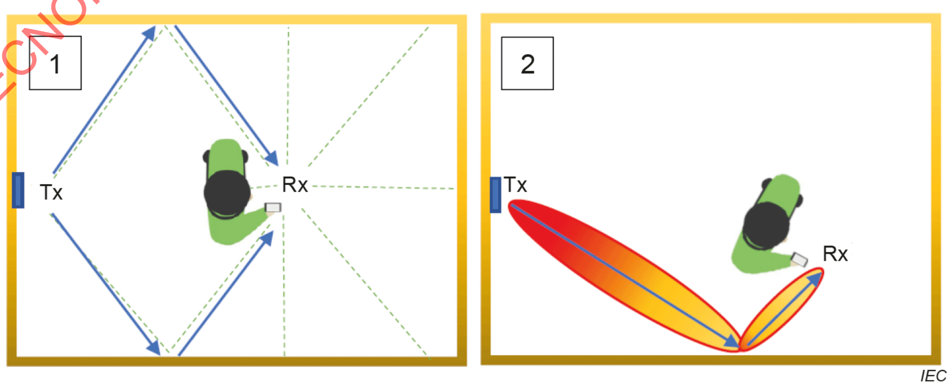


Figure 3 – Beam pattern diagram of space diversity WPT

5.2.3 Operating principle of narrow-beam WPT

Antenna arrays are typically used for narrow-beam radiative WPT systems. As illustrated in Figure 4, the transmitter can transfer power at a distance to one or multiple receivers, by directing the beam patterns using beamforming techniques. The beamforming techniques consist of controlling the amplitudes and/or phases between radiating signals of the antenna array.

Both space diversity WPT and narrow-beam radiative WPT utilize the antenna beamforming technology but in different ways. Space diversity WPT illustrated in Figure 3 is implemented by making use of the multi-path reflection from the walls to deliver the power to the receiver "around" the human body or object. On the other hand, the narrow-beam radiative WPT system typically operates as a point-to-point power transmission to a receiver. Beamforming technique is used to increase the gain of the transmitting array antenna to extend the operational distance of WPT. If a person moves to a line-of-sight between transmitter and receiver, the RF transmission stops.

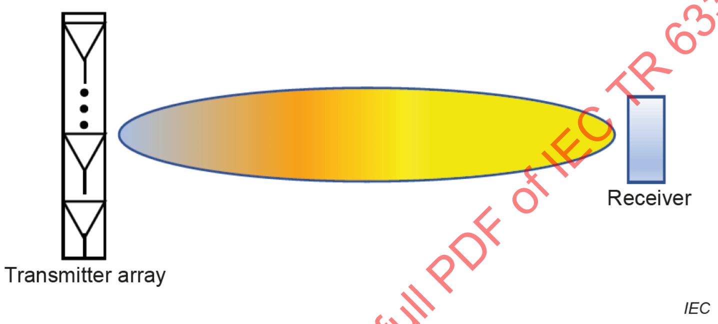


Figure 4 – Beam pattern diagram of narrow-beam radiative WPT

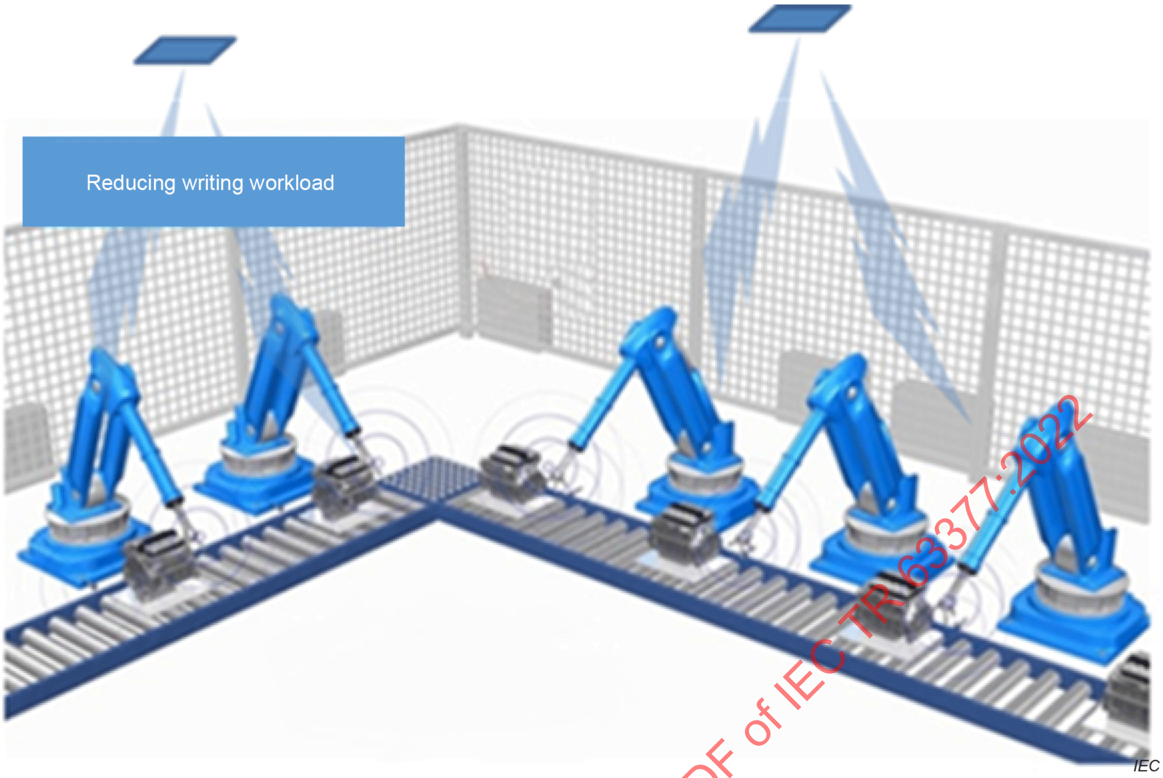
5.3 Use cases and environment

5.3.1 General

Use cases and those environments where radiative WPT systems are used are important in order to discuss exposure assessment and other RF exposure items. The environments described in 5.3.2, 5.3.3, 5.3.4, and 5.3.5 are considered.

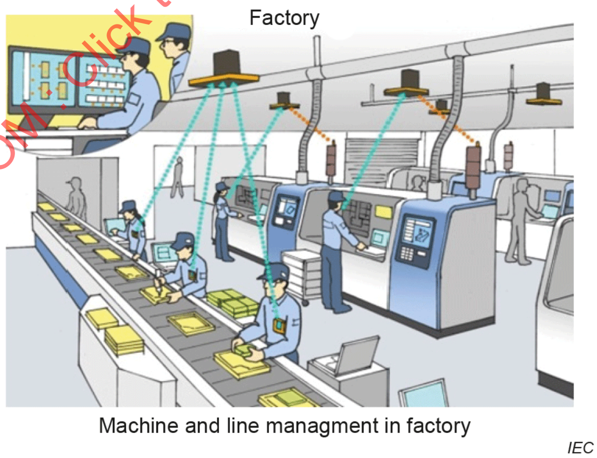
5.3.2 Indoor, occupational environment

Figure 5 and Figure 6 show typical use cases in indoor and occupational environments. In these use cases, sensors and devices which received power by radiative WPT systems are generally located far from human bodies (Figure 5). In some cases, radiative WPT systems are used in an environment with humans (Figure 6). The radiated power is generally small outside of buildings and/or rooms.



[SOURCE: Figure 2.3.5(a) of Report for the technical conditions of beam WPT, MIC, Japan [11][3]

Figure 5 – Example of indoor and occupational environments: WPT to production equipment sensors in factory



[SOURCE: Figure 2.3.1(a) of Report for the technical conditions of beam WPT, MIC, Japan [11][4]

Figure 6 – Example of indoor and occupational environments: WPT to machine and line management sensors

[3] Reproduced from the Report for the technical conditions of beam WPT, MIC, Japan, with the permission of the Ministry of Internal Affairs and Communications, Japan.

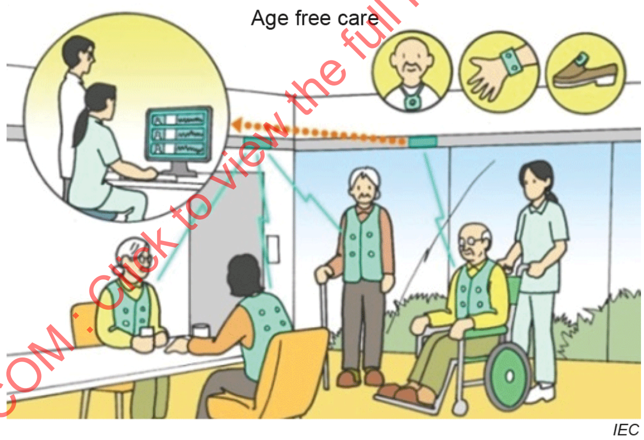
[4] Reproduced from the Report for the technical conditions of beam WPT, MIC, Japan, with the permission of the Ministry of Internal Affairs and Communications, Japan.

5.3.3 Indoor, general-public environment

Figure 7 and Figure 8 show typical use cases in indoor and general-public environments. In these use cases, sensors and devices which received power by radiative WPT systems are located near human bodies or within close contact. The radiated power is generally small outside of buildings and/or rooms.

[SOURCE: Figure 2.3.2(b) of Report for the technical conditions of beam WPT, MIC, Japan [11]][5]

Figure 7 – WPT to children watching sensors



[SOURCE: Figure 2.3.1(c) of Report for the technical conditions of beam WPT, MIC, Japan [11]][6]

Figure 8 – WPT to watching sensors in nursing homes

5.3.4 Outdoor, occupational environment

Sensors and devices for industrial applications can be used in outdoor and in occupational environments. In such cases, sensors and devices which received power by radiative WPT systems are located far from human bodies or used in an environment without humans.

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5 Reproduced from the Report for the technical conditions of beam WPT, MIC, Japan, with the permission of the Ministry of Internal Affairs and Communications, Japan.

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5.3.5 Outdoor, general-public environment

In this use case, sensors and devices which received power by radiative WPT systems are located near human bodies or within close contact. There are some possibilities that the unwanted power could be radiated in an open space.

6 General exposure assessment considerations

6.1 General

This Clause 6 describes the basis for exposure assessments. Figure 9 shows the steps of an exposure assessment for radiative WPT systems, including preparation of the assessment, measurements or calculations and uncertainty.

Some form of proximity sensing can be used to detect the presence of a person within the exposed area. This information is used to lower the transmitted power or modify the beam direction to reduce the maximum exposure. Time-period power control reduces the maximum output power of the antenna after a fixed period of time to keep the exposure below the limit over the specified averaging time. The technologies and methods for evaluating the effect of mitigation techniques such as the proximity sensor and time-period power control are described in Annex C.

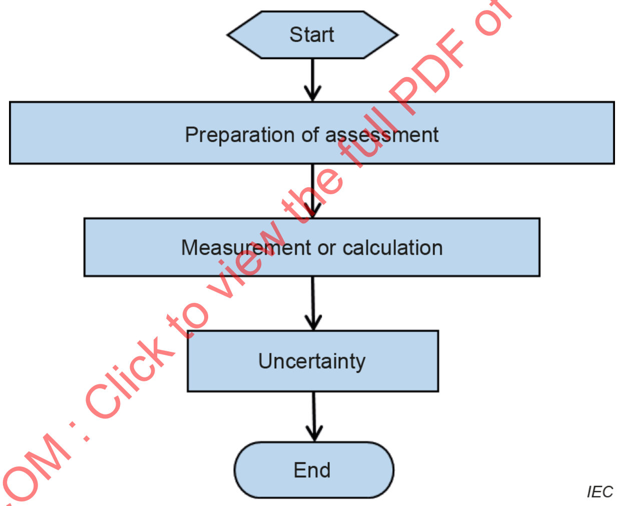

Figure 9 – Assessment process for radiative WPT

6.2 Preparation of assessment

6.2.1 General

In preparation for the assessment, the key parameter, limit set, and assessment method are determined.

6.2.2 Determination of key parameters

6.2.2.1 General

To perform an exposure assessment, it is necessary to determine the assessment purpose, assessment region, and RF emission characteristics of the considered device. Examples of radiative WPT systems are shown in Clause 5.

6.2.2.2 Assessment purpose

Assessment purposes are summarized in Clause 6 of IEC 62232:2017 [12]. For the assessment of radiative WPT systems, the purpose is divided into two parts:

- Product compliance,
- Product installation compliance.

For product compliance, a manufacturer or other legal entity that will provide a WPT product on the market is typically required to provide RF exposure information to the end user of the product. In this case, the assessment is performed in the appropriate experimental site, such as anechoic chamber, near-field test labs, SAR labs, etc., before it is placed on the market.

For product installation compliance, an installer of WPT products is typically required to provide RF exposure information to the end user of the product. It requires the determination of the total exposure levels in accessible areas from the product. The assessment is performed in the real environment of the device including indoor and outdoor situations. In such an evaluation, contributions from other relevant sources and possible effects of the environment are considered.

For consumer type products, in the user manual, the user is made aware in what conditions the radiative WPT devices are tested and therefore deemed compliant. The product is used as per the condition set for compliance testing.

Devices can be excluded from testing if their maximum output power is below the threshold described in IEC 62479:2010 [13].

6.2.2.3 Assessment region

Characteristics of the electromagnetic fields from the WPT device highly depend on the distance from the device. Therefore, the exposure region can be classified into three different distances from the device:

– the reactive near-field of the source,

– the radiating near-field of the source,

– the far-field of the source.

For an accurate assessment, an appropriate method is selected for each region.

The maximum human exposure can occur in the close near-field as well as at greater distances (≫ several metres) from the transmitter. The effects of tissue layering and partial-body resonances can be excluded for distances closer than 200 mm. Additional coupling factors are considered for greater distances when simplified homogeneous bodies are applied for the exposure assessment. These coupling factors are described in Annex A. Signal coherence for induced fields can occur at any distance.

6.2.3 Determination of applicable limits

At frequencies above 30 MHz, the dominant effect of electromagnetic field exposure is known to be thermal. There are international guidelines and standards regarding human safety due to exposure, e.g., [5], [14], [15], [16]. The basic restriction (or DRL) is established based on the thresholds for established health effects as the specific absorption rate or the absorbed (epithelial) power density. The reference level (or ERL) is also provided as the equivalent level of protection to the basic restriction for conservative-case exposure scenarios. The limit set depends not only on the assessment region and frequency range but also on the exposure situation such as whole-body exposure and local exposure. Both whole-body exposure and local exposure need to satisfy the guideline limits simultaneously.

NOTE 1 ICNIRP guidelines of 1998 [14] are still referenced by many national authorities.

NOTE 2 There are some differences in the exposure metric for the radiative WPT systems for whole-body and local exposure in other RF exposure guidelines such as Health Canada Safety Code 6 [17]. For instance, in the reactive near-field, E-field and H-field reference levels are specified.

6.2.4 Determination of assessment method

6.2.4.1 General

The assessment method is selected considering the exposure metrics and the applicability of the assessment methods. The process to determine the assessment method is summarized in Clause 7 of IEC 62232:2017 [12].

RF field strength, power density, SAR or a combination of these metrics can be evaluated by measurement and computation. If specific assessment methods are specified in IEC 62232:2017 [12], these specifications can be used for WPT. When defining the assessment configuration, national (e.g., regulatory and legislative) requirements can apply. Computational standards for exposure assessment in terms of SAR are IEC/IEEE 62704-1:2017 [18] and IEC/IEEE 62704-4:2020 [19].

Measurement instrumentations and computational tools and their validations are already described in other standards for the same frequency range. A standard for assessing the local absorbed (or epithelial) power density is not available at the time of publication of this document. The development of such standards is envisaged in the future. In many cases, the assessment of the exposure by radiative WPT systems is most effectively completed by combining computation with measurement procedures, e.g., determination of the maximum exposure configuration and distance by computation and determination of the actual exposure by measurements. Maximum exposure assessment methods have also been proposed in Annex C of IEC/IEEE 63195-2:2022 [20].

6.2.4.2 RF field strength and power density measurements

RF field strength and power density measurement are applicable for both product compliance and product installation compliance without presence of a human body. In the reactive and radiating near-field, both the incident E-field and H-field need to be measured and both need to be compliant with the reference levels. The same applies for far-field if the values are compared to the plane-wave equivalent power density. The requirements for the laboratory base field strength and power density measurements are summarized in Clause B.3 of IEC 62232:2017 [12].

For local exposure over 6 GHz, the power density measurement requirements described in IEC/IEEE 63195-1:2022 [2] can be applied. The same method can be used to verify that the measurement systems operate within their specifications.

The methods for evaluating RF fields strength and power density are summarized in Annex B.

6.2.4.3 SAR measurements

In the reactive and radiating near-field of sources and up to 6 GHz, SAR measurement procedures can be applied, which generally results in lower overestimation than RF field strength measurements. SAR measurements are not constrained to the field characteristics. At distances less than 200 mm, the SAR measurement for both whole-body exposure and local exposure can be performed using measurement equipment and procedures described in IEC 62232:2017 [12] and IEC/IEEE 62209-1528:2020 [3], respectively. For greater distances up to 1 000 mm, the procedures as described in IEC 62232:2017 [12] can be applied. The SAR measurement procedures as described in IEC 62232:2017 [12] have no technical limitations that would prevent their applicability at greater distances. Hence, they can be applied at distances greater than 1 000 mm.

For local SAR, the SAR measurement requirements as described in IEC/IEEE 62209-1528:2020 [3] can be applied to demonstrate compliance with SAR limits. More information is provided in Annex B.

The detailed explanation for whole-body SAR measurement is described in Clause B.3 of IEC 62232:2017 [12]. If the maximum RF transmit power of the product is less than the values specified in Table 2, it is not necessary to perform whole-body SAR measurement.

NOTE IEC 62232:2017 [12] describes whole-body SAR measurement from 300 MHz to 6 GHz. Development of a measurement method below 300 MHz is necessary.

Table 2 – Whole-body SAR exclusions based on RF power levels

Exposure condition	**Maximum transmitted RF power** [W]
General public exposure	General public whole-body SAR limit [W/kg] × 12,5 [kg]
Occupational exposure	Occupational whole-body SAR limit [W/kg] × 46 [kg]

NOTE The whole-body SAR exclusion power levels have been derived based on the following assumptions: 1) all of the power emitted from the antenna is absorbed in the body, 2) children below the age of 4 years do not have access to the antenna at a distance of less than 20 cm and 3) the body masses for a 4-year-old child (12,5 kg) and a 16-year-old worker (46 kg) have been derived from body weight statistics published by WHO [21] and US National Center for Health [22].

6.2.4.4 Computational methods

The relevant computational methods for RF field strength, power density and SAR assessment are summarized in Clause B.4 of IEC 62232:2017 [12]. There are two types of computational methods. One is basic computations to assess RF field strength, power density, or SAR by conservative formulas specified for far-field with a spherical coordinate system, which do not require uncertainty estimations and can be utilized in certain limited applications. The RMS electric field strength E and magnetic field strength H can be evaluated using Formula (2) and Formula (3)

$$E = \frac{\sqrt{30\overline{P_{\text{net}}}G_{\theta,\phi}}}{r} \tag{2}$$

$$H = \frac{E}{\eta_0} \tag{3}$$

while the spatial-peak equivalent power density can be calculated per Formula (4)

$$S = \frac{\overline{P_{\text{net}}}G_{\theta,\phi}}{4\pi r^2} \tag{4}$$

where $\overline{P_{\text{net}}}$ and $G_{\theta,\phi}$ are net average power transferred into the antenna port and antenna directive gain in the main beam, respectively.

NOTE For the estimate of S, E, or H to be conservative, $\overline{P_{\text{net}}}$ and $G_{\theta,\phi}$ values are the upper bounds of the uncertainty (see B.4.2.1.1.2 of IEC 62232:2017 [12]).

To consider reflection from ground plane, S can be calculated per Formula (5)

$$S = \left(1+\left|\Gamma\right|\right)^2 \frac{\overline{P_{\text{net}}}G_{\theta,\phi}}{4\pi r^2} \tag{5}$$

with reflection coefficient $|\Gamma| = 1$ for the perfectly conducting plane and $|\Gamma| = 0,6$ for typical ground reflection condition. Use of the far-field spherical formulas in the near-field region will overestimate the field strength levels. This is especially true in the calculation of field quantities of the radiative WPT transmitter operating at microwave (over 900 MHz) frequency bands. In such a case, the conservativeness of the calculations is ensured. However, in WPT implementations at 30 MHz when inductive coupling is used in the reactive near-field region Formula (2) through Formula (5) cannot be considered conservative.

The second method uses the advanced computations for some scenarios where more accurate assessments are required. The examples include field calculations in the near-field of an antenna and SAR assessments to the side of the transmitting antenna. The advanced computational methods are presented in B.4.4 of IEC 62232:2017 [12]. Full uncertainty analysis is carried out if an advanced technique is used.

Computational SAR assessment can be applied as described in IEC/IEEE 62704-1:2017 [18] or IEC/IEEE 62704-4:2020 [19] to demonstrate compliance with peak spatial SAR limits, deviations from which are described in this document. Whole-body exposures are evaluated according to IEC 62232:2017 [12]. More information is given in Annex B.

Computational assessment of the power density for local exposure over 6 GHz is applied as described in IEC/IEEE 63195-2:2022 [20]. Computational methods are introduced in Annex D.

6.3 Assessment conditions

The assessment is valid for any distance and location where a human could be exposed to the fields emitted by the radiative WPT system. In the far-field zone of a beam-forming transmitting antenna (field impedance of 377 Ω), the assessment is performed within the broad area covering not only the main beam but also all the side lobes of antenna radiation pattern. In the case of a broad radiation pattern, it is necessary to evaluate the whole-body exposure. At the distances corresponding to the reactive near-field and radiating near-field zones where the field impedance can deviate from 377 Ω, the cases of local body exposure with the relevant applicable RF exposure limits (E-field and H-field, power density, psSAR, etc.) are evaluated. Following this procedure, maximum values of E-field and H-field are recorded by the appropriate assessment method. Depending on the applicable conditions for WPT environment, the assessment can also consider possible reflections from the objects located close to the transmitter or the effects of backscattering. During the assessment process, the transmitted power is fixed at the maximum operating power output level of EUT.

6.4 Uncertainty

The exposure assessment includes comprehensive uncertainty budgets for the frequency ranges from 30 MHz to 6 GHz and above 6 GHz that have been determined for the specific exposure situations. These uncertainty budgets are described in detail in IEC/IEEE 62209-1528:2020 [3] and IEC/IEEE 63195-1:2022 [2], respectively. They include at least the parameters listed in Table 3 for the psSAR for frequencies from 30 MHz to 6 GHz and in Table 4 for the incident power density at > 6 GHz. The clauses and subclauses of IEC/IEEE 62209-1528:2020 [3] and IEC/IEEE 63195-1:2022 [2] that describe how to evaluate the uncertainty sources are referenced in Table 3 and Table 4 of this document.

IEC 62311:2019 recommends a relative expanded uncertainty (k = 2) of ±30 % (−1,55 dB, +1,14 dB) as permissible maximum value of the uncertainty budget for EMF assessment. This uncertainty value applies to electronic and electrical equipment for which no dedicated product or product family standard regarding human exposure to electromagnetic fields applies.

For power density assessment over 6 GHz requiring amplitude and phase assessments of the electric field and magnetic field in the near-field of sources, IEC/IEEE 63195-1:2022 recommends a relative expanded uncertainty (k = 2) of ±2 dB (−37 %, +58 %) as the permissible maximum value of the uncertainty budget for power density assessment between 6 GHz to 300 GHz.

If the assessment uncertainty is less than or equal to the permissible maximum uncertainty, then the measured value can be compared directly with the applicable limit for the assessment of compliance.

Where acceptable by national requirements, if the expanded uncertainty is greater than the permissible maximum uncertainty, the reported data needs to take into account the percentage difference between the actual uncertainty and the permissible maximum uncertainty (see IEC 62311:2019 [4] for details).

Table 3 – Template of measurement uncertainty budget for assessment of the psSAR for frequencies from 30 MHz to 6 GHz

Source of uncertainty	**Ref. of IEC/IEEE 62209-1528:2020**	**Prob. Dist.[a]** PDF_i	**Unc.** $a(x_i)$	**Div.[a]** q_i	$u(x_i) = a(x_i)/q_i$	c_i	$u(y) = c_i \cdot u(x_i)$	v_i
Measurement system errors								
Probe calibration	8.4.1.1							
Probe calibration drift	8.4.1.2							
Probe linearity and detection limit	8.4.1.3							
Broadband signal	8.4.1.4							
Probe isotropy	8.4.1.5							
Other probe and data acquisition errors	8.4.1.6							
RF ambient and noise	8.4.1.7							
Probe positioning errors	8.4.1.8							
Data processing errors	8.4.1.9							
Phantom and device errors (EUT or validation antenna)								
Measurement of phantom conductivity(σ)	8.4.2.1							
Temperature effects (medium)	8.4.2.2							
Shell permittivity	8.4.2.3							
Distance between the radiating element of the EUT and the phantom medium	8.4.2.4							
Repeatability of positioning the EUT or source against the phantom	8.4.2.5							
Device holder effects	8.4.2.6							
Effect of operating mode on probe sensitivity	8.4.2.7							
Time-average SAR	8.4.2.8							
Variation in SAR due to drift in output of EUT	8.4.2.9							
Validation antenna uncertainty (validation measurement only)	8.4.2.10							
Uncertainty in accepted power (validation measurement only)	8.4.2.11							
Corrections to the SAR result (if applied)								
Phantom deviation from target (ε',σ)	8.4.3.1							
SAR scaling	8.4.3.2							
Combined uncertainty								
Expanded uncertainty (k = 2) and effective degrees of freedom								

[a] Other probability distributions and divisors may be used if they better represent available knowledge of the quantities concerned.

Table 4 – Template of measurement uncertainty budget for assessment of the incident power density for frequencies above 6 GHz

Source of uncertainty	Ref. of IEC/IEEE 63195-1:2022	Prob. Dist.[a] PDF_i	Unc. $a(x_i)$	Div.[a] q_i	$u(x_i)$ = $a(x_i)/q_i$	c_i	$u(y) = c_i \cdot u(x_i)$	v_i
Uncertainty terms dependent on the measurement system								
Calibration	8.4.1							
Probe correction	8.4.2							
Frequency response	8.4.3							
Sensor cross coupling	8.4.4							
Isotropy	8.4.5							
System linearity error	8.4.6							
Probe scattering	8.4.7							
Probe positioning offset	8.4.8							
Probe positioning repeatability	8.4.9							
Sensor mechanical offset	8.4.10							
Probe spatial resolution	8.4.11							
Field impedance dependence	8.4.12							
Measurement drift	8.4.13							
Amplitude and phase noise	8.4.14							
Measurement area truncation	8.4.15							
Data acquisition	8.4.16							
Sampling	8.4.17							
Field reconstruction	8.4.18							
Signal-to-noise ratio	8.4.19							
Forward and backward transformation	8.4.20							
Power density scaling	8.4.21							
Spatial averaging	8.4.22							
Exposure combining	8.4.23							
Uncertainty terms dependent on the EUT and environmental factors								
Probe coupling with EUT	8.5.1							
Modulation response	8.5.2							
Integration time	8.5.3							
Response time	8.5.4							
Device holder influence	8.5.5							
EUT alignment	8.5.6							
RF ambient conditions	8.5.7							
Laboratory temperature	8.5.8							
Reflections in laboratory	8.5.9							
Immunity / secondary reception	8.5.10							
EUT drift	8.5.11							
Combined standard uncertainty	8.6							
Expanded uncertainty (k = 2) (95 % confidence interval)	8.6							

Determination of the reconstruction and forward/backward transformation directly using actually measured or simulated measured data such that uncertainty propagation and SNR is already considered.

[a] Other probability distributions and divisors can be used if they better represent available knowledge of the quantities concerned.

Annex A
(informative)

Coupling factors and correction factors

A.1 General

Limits on human exposure to electromagnetic fields are established in terms of basic restrictions and reference levels (e.g., [5], [14], [15], [16], [23]). Basic restrictions refer to quantities that describe the electromagnetic fields induced inside the human tissues. Reference levels refer to the incident fields in free space. The assessment of basic restrictions requires the representation of the human body, e.g., by an appropriate anatomical computational model or by a mannequin or phantom depending on whether computational or experimental methods are applied. The assessment of the electromagnetic field exposure with respect to the reference levels only requires the quantification of the incident field to which users or bystanders are exposed.

This annex describes coupling factors for the near-field (Clause A.2) and correction factors for the far-field (Clause A.3):

- The coupling factors (F_{cpl}) for near-field-like exposure describe the coupling mechanism that correlates the fields in free space with those induced in the body, i.e. the dominant parameters for a particular exposure situation required for a conservative exposure estimate.
- The correction factors (F_{cor}) take into account a possible increase in the SAR due to the tissue layering effects, or due to partial-body resonances in heterogeneous human body models when the transmitter is placed at distances greater than 200 mm from the exposed subject where far-field effects dominate.
- The dominant characteristics of the incident field that the coupling mechanism depends on are:
  1) frequency;
  2) physical field component (electric field and/or magnetic field, power density);
  3) polarization and angle of incidence;
  4) electrical distance from the field source,
- Anatomical parameters that are relevant for the quantification of the fields induced in the body are:
  1) body height and volume or body mass index (BMI);
  2) posture of the body and limbs;
  3) length of the limbs and other body parts, such as fingers, relative to the wavelength;
  4) grounding conditions and termination of the limbs;
  5) dielectric tissue parameters;
  6) tissue composition and layering,
- The interaction of the incident field and the exposed body is characterized by:
  1) electric loading of the near-field (i.e. interaction of the source and body) by the presence of the exposed body as a scatterer;
  2) standing wave effects due to possible reflections from the field source and the body in the far-field.

For radiative WPT systems only a subset of the parameters listed above is relevant. Within the scope of this document, user exposure can be both near- and far-field conditions, as well as whole-body or partial-body or very localized exposure. The coupling mechanisms considering this range of characteristics of the radiative WPT systems under typical and worst-case exposure situations are reviewed in Clause A.2 to Clause A.4.

A.2 Coupling factors for near-field exposure

A.2.1 Characteristics of the near-field

In the reactive near-field of an electromagnetic field source, the E-fields and H-fields are determined by the charge distribution or current distribution on the elements of the EUT that conduct RF energy, such as antennas, ground planes or open transmission lines. A significant part of the electromagnetic energy in the near-field belongs to the reactive field, i.e., it does not propagate away from the field source. Typically, the Poynting-vector in the near-field is complex and changes its direction when regarded as a function of time. The E-field and H-field are not directly coupled, and a person could be exposed to only one dominant field component. For the WPT systems within the scope of this document, near-field conditions are considered at the lower end of the specified frequency range, which makes the application of separate coupling factors necessary, i.e., $F_{\text{cpl E}}$ for E-field and $F_{\text{cpl H}}$ for H-field.

The transition range from near- to far-field occurs in a range from $R = 0{,}62\sqrt{D^3/\lambda}$ to $R = 2D^2/\lambda$ and is referred to as the Fresnel zone [24]. Recent studies on the absorption of electromagnetic fields in the human body have shown that far-field effects are already dominant at distances of $\lambda/(2\pi)$, which corresponds to a range of approximately 0,16 mm to 1,6 m for the upper frequencies of the range within the scope of this document [25], [26].

A.2.2 Coupling of electromagnetic energy in the near-field

In the near-field of antennas or other RF conductors, the fields induced in the human body are mainly caused by eddy currents. These are induced by the incident magnetic field. Hence, the coupling mechanism that describes the absorption is based on the RF currents that give rise to the magnetic field and the tissue conductivity. Absorption of RF energy mainly occurs in tissues with higher water content, such as skin, muscle or brain tissue above 300 MHz. Details can be found in [27].

Capacitive coupling can occur in situations where charges are accumulated at fractions of wavelengths (< $\lambda/10$), e.g., at the antenna tips. If the minimal distance from the radiative WPT source is greater than $\lambda/10$, capacitive coupling is not considered.

A.2.3 Considerations for whole-body exposure in the near-field

Radiative WPT systems operating at the lower end of the frequency range covered in this document or geometrically large antenna arrays can expose larger body areas or the entire body to their reactive near-field. For E-fields polarized parallel to a limb or the body axis, resonance effects are likely to occur in a way that is similar to far-field exposure.

A.2.4 Derivation of the coupling factors for E-field or H-field exposure

To derive independent coupling factors $F_{\text{cpl E}}$ and $F_{\text{cpl H}}$ for assessment of the induced fields in a human body for frequencies of 30 MHz and above, the body model is exposed to E-fields and H-fields independently.[7] $F_{\text{cpl E}}$ and $F_{\text{cpl H}}$ quantify the ratio of the incident E-field or H-field amplitude and the induced SAR in the body. They can be determined by quantifying the induced fields as a function of either the incident E-field or H-field. Such field conditions can be obtained by exposing a body model to:

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7 For correction factor and coupling factor quantities, this document uses a notation of variable symbol F with subscripts. Such notation is consistent with IEC 60027-1 and ISO/IEC Directives Part 2 principles.

– superimposed propagating plane waves with localized E-field or H-field maxima and the corresponding H-field or E-field minima, respectively,
– exposure to a reactive plane wave component having a wave impedance significantly higher or lower than the free-space wave impedance [28].

Derivations of $F_{\text{cpl E}}$ and $F_{\text{cpl H}}$ can be carried out numerically or analytically. Depending on the characteristics of the body model or phantom for which $F_{\text{cpl E}}$ and $F_{\text{cpl H}}$ are determined, the correction factors F_{cor1}, F_{cor2}, or F_{cor3} described in Clause A.3 might need to be considered additionally.

For both options, the field amplitude is not constant over the exposed domain. The reactive plane waves decay rapidly, which corresponds to their real world characteristics.

The complex dielectric properties of the exposed body characterize transmission, penetration and absorption of the electric or magnetic field energy. As the permeability of the body is identical to free space, magnetic fields can be assumed to penetrate easily. Hence the tissue conductivity is the relevant quantity that determines the coupling factor if the incident magnetic field is dominant [27]. For characterization of $F_{\text{cpl E}}$, the dielectric contrast between the body and free space are considered.

A conservative assessment of the coupling factors mainly considers the dielectric properties and composition of the tissues. Enhancement of the coupling due to resonances can occur for near-field exposure, e.g., due to induced currents if the body or its subregions (limbs, fingers) have an approximate length of $\lambda/2$ or $\lambda/4$ depending on their termination or grounding.

A.3 Correction factors for far-field exposures

A.3.1 Characteristics of the far-field

In the far-field region, the Poynting vector (which is the vector product of the electric field vector and the magnetic field vector) has a negligible imaginary part; i.e. it is constant over a period T_0 of the signal (where $T_0 = 1/f_{\text{signal}}$), and its direction is away from the transmitter. The ratio of the electric field and magnetic field amplitudes corresponds to the free-space wave impedance, and the body is exposed to propagating E-fields and H-fields simultaneously. With respect to the exposure of the human body, far-field effects are dominant at distances above $\lambda/(2\pi)$ [25], [26], [29].

NOTE Because some WPT systems control the direction of their transmitting beam, the direction of the Poynting vector can change as a function of time. The time scale of these changes can be assumed to be significantly greater than T_0.

A.3.2 Tissue layering

With respect to their dielectric properties at RF, body tissues can be categorized into those with high water content, such as skin, muscle, or brain tissue and those with low water content, such as bone, fat and the stratum corneum. In body regions with mainly stratified tissue, such as the torso, standing wave effects can occur in sequences of tissue layers with alternating water content, such as skin tissue followed by a fat layer that is electrically terminated in a muscle layer. For fat layer thicknesses of approximately $\lambda/4$, constructive interference (matching effects) can lead to an increase in local absorption in the skin layer, [30], [31], which can cause an increase of the psSAR by more than 2 dB in comparison to the homogeneous tissue. These effects can also have an impact on the whole-body SAR and are considered in Clause A.1. These effects are relevant for frequencies up to approximately 10 GHz.

Above 10 GHz, absorption occurs in the layers of the skin tissue because of the lower penetration depth. Moreover, the conductivity of fat tissue increases leading to additional absorption. Hence, constructive interference effects in the different tissue layers are no longer relevant for the absorption [26]. Body regions with a higher stratum corneum thickness, such as the palm or the soles of the feet, can lead to impedance matching effects and an increase in the absorption of RF energy by approximately 3 dB [31].

A.3.3 Whole-body absorption and resonance

Whole-body absorption can be estimated by calculating the absorption in a prolate spheroid phantom [32]. This strongly simplified model of the human body serves as a basis to determine the correlation of the basic restriction on the whole-body SAR with the incident field strength or power density [5], [12], [15]. While the prolate spheroid phantom considers the absorption enhancement at the resonance frequency of the body, more recent studies have shown that it underestimates the exposure of children under resonance conditions [33]. However, radiative WPT systems mostly require focusing of the energy on the receiving elements in order to be energy efficient, which leads to partial exposure of the body only. In these cases, whole-body resonances do not have to be considered, and the whole-body SAR is evaluated as described in A.4.3. Partial-body absorption is considered according to A.4.4.

A.3.4 Conservative correction factors

Conservative correction factors ($F_{\text{cor}i}$) accounting for tissue layering effects are specified in B.3.2.3 of IEC 62232:2017 [12] for whole-body plane wave-like exposures in the frequency range of 300 MHz to 6 GHz, and are summarized in Table A.1.

Table A.1 – Summary of correction factors accounting for tissue layering effects specified in IEC 62232:2017 [12] for psSAR and wbSAR[8]

Distance d source-object	psSAR $F_{\text{cor1}}(d)$	wbSAR $F_{\text{cor2}}(d)$
d < 200 mm	1	1 + 0,8 d / 400
200 mm ≤ d < 400 mm	d / 200	1 + 0,8 d / 400
d ≥ 400 mm	2	1,8

The corrected psSAR and wbSAR, $SAR_{\text{ps cor}}$ and $SAR_{\text{wb cor}}$, are determined according to Formula (A.1) and Formula (A.2).

$$SAR_{\text{ps cor}}(d) = SAR_{\text{m}}(d) \times F_{\text{cor1}}(d) \quad \text{(A.1)}$$

$SAR_{\text{m}}(d)$ is the uncorrected measured peak spatial-average SAR, averaged over either 1 g (SAR_{1g}) or 10 g (SAR_{10g}), d is the EUT distance (mm) measured from the liquid surface, and $F_{\text{cor}i}(d)$ corresponds to $F_{\text{cor1}}(d)$ or $F_{\text{cor3}}(d)$ depending on the human body part; see Clause A.4.

$$SAR_{\text{wb cor}}(d) = \frac{P_{\text{A}}(d) \times F_{\text{cor2}}(d)}{M} \quad \text{(A.2)}$$

where

$P_{\text{A}}(d)$ is the average temporal absorbed power (W) in the phantom, measured at d,

d is the EUT distance (mm) measured from the liquid surface, and

M is the mass of the body (kg).

8 Further to IEC 60027-1 and ISO/IEC Directives Part 2 principles, this document uses the notation $F_{\text{cor}i}$ rather than for example CF_i as in IEC 62232:2017.

$F_{\text{cor3}}(d)$ can be different for localized exposures. The procedure for determining these factors for specific radiative WPT systems is explained in Clause A.4.

A.4 Assessment of correction factors for layered tissues

A.4.1 General

SAR assessment results in homogeneous box-shaped phantoms can be compared to SAR in anatomical human body models to estimate enhancement (correction) factors $F_{\text{cor}i}$ due to the effects of layered tissues, with $F_{\text{cor}i} \geq 1$. Comparisons are performed between the maximum SAR found in a human anatomical model with respect to that in a homogeneous flat-surface box phantom. The size of the homogeneous flat phantom is close to that of the human anatomical model; for example, child anatomical models are compared to a child-sized flat box-shaped phantom.

A.4.2 Correction factors for peak-spatial average SAR

F_{cor1} accounts for possible enhancement effects on the maximum psSAR estimated in a homogeneous flat phantom due to tissue layering, per Formula (A.3):

$$F_{\text{cor1}}(d) = \begin{cases} \dfrac{SAR_{\text{ps child torso}}}{SAR_{\text{ps child phantom}}} \\ \dfrac{SAR_{\text{ps adult torso}}}{SAR_{\text{ps adult phantom}}} \end{cases}, \ 200 \text{ mm} \leq d \leq 1\,000 \text{ mm} \qquad \text{(A.3)}$$

In the subscripts, torso refers to the anatomical (heterogenous) model, and phantom refers to the homogeneous model, and d is the EUT distance (mm) measured from the body or phantom surface.

A.4.3 Correction factors for whole-body SAR

F_{cor2} accounts for possible enhancement effects on maximum wbSAR estimated in a homogeneous flat phantom due to tissue layering, per Formula (A.4):

$$F_{\text{cor2}}(d) = \begin{cases} \dfrac{SAR_{\text{wb child}}}{SAR_{\text{wb child phantom}}} \\ \dfrac{SAR_{\text{wb adult}}}{SAR_{\text{wb adult phantom}}} \end{cases}, \ 200 \text{ mm} \leq d \leq 1\,000 \text{ mm} \qquad \text{(A.4)}$$

A.4.4 Correction factors for partial body exposures

Because the maximum psSAR can occur in small regions of the body, e.g., in the limbs, an additional correction factor F_{cor3} can be calculated per Formula (A.5):

$$F_{\text{cor3}}(d) = \begin{cases} \dfrac{SAR_{\text{ps child limb}}}{SAR_{\text{ps child phantom}}} \\ \dfrac{SAR_{\text{ps adult limb}}}{SAR_{\text{ps adult phantom}}} \end{cases}, \ 200 \text{ mm} \leq d \leq 1\,000 \text{ mm} \qquad \text{(A.5)}$$

A.4.5 Correction of SAR results in homogeneous flat phantoms

A.4.5.1 Assessment of maximum peak spatial-average SAR in the torso

The psSAR estimated in a homogeneous flat phantom by either computational or experimental methods can be corrected in accordance with Formula (A.6):

$$SAR_{\text{ps torso}}(d) = SAR_{\text{ps phantom}}(d) \times F_{\text{cor1}}(d) \tag{A.6}$$

A.4.5.2 Assessment of maximum peak spatial-average SAR in the extremities

The psSAR estimated in a homogeneous flat phantom by either computational or experimental methods can be corrected in accordance with Formula (A.7):

$$SAR_{\text{ps extremities}}(d) = SAR_{\text{ps phantom}}(d) \times F_{\text{cor3}}(d) \tag{A.7}$$

A.4.5.3 Whole-body SAR measurement description

The wbSAR estimated in a homogeneous flat phantom by either computational or experimental methods can be corrected in accordance with Formula (A.8):

$$SAR_{\text{wb}}(d) = SAR_{\text{wb phantom}}(d) \times F_{\text{cor2}}(d) \tag{A.8}$$

Annex B
(informative)

Assessment procedure

B.1 RF field strength and power density assessment for radiative WPT systems

The incident exposure can be evaluated by measuring the incident E-field and H-field distributions in the exposure volume and comparing both to the reference levels. In the far-field, it is sufficient to measure only the E-field or H-field or the plane-wave equivalent power density and compare the values to the reference levels. This can be performed by a robot system or by a maximum-hold sweep technique as described in B.3.1.2.5.2 of IEC 62232:2017 [12]. If the conditions for the applicability of spatial averaging are satisfied (IEC 62232:2017 [12]), the spatial averaging scheme as described in B.3.1.4 of IEC 62232:2017 [12] can be applied. A similar procedure can also be used in the radiating near-field zone where the maximum recorded values of E-field or H-field are to be used by the sweeping method. The assessment is performed in a well-specified reflective environment simulating an installation case with conservative exposure. Justification of the selected approach is provided.

The spatial distribution of the field at the position of a body depends on propagation conditions including reflections from the floor, walls and objects in the environment. In some situations, the spatial distribution will be dominated by the direct field from the transmitting antenna or in combination with a ground reflected wave. In an indoor environment, the distribution is strongly affected by multiple reflections from the floor and the walls and it is therefore recommended that the received RF field should be evaluated in the laboratory conditions where multiple reflections from the objects are utilized. The same conditions are included in the EM simulation model used for the computational assessment.

Two examples of WPT exposure assessments are introduced in Annex E.

B.2 Local SAR assessment for radiative WPT systems operating between 30 MHz to 6 GHz

B.2.1 General

The procedure described in B.2.2 to B.2.4 is summarized in the flowchart of Figure B.1.

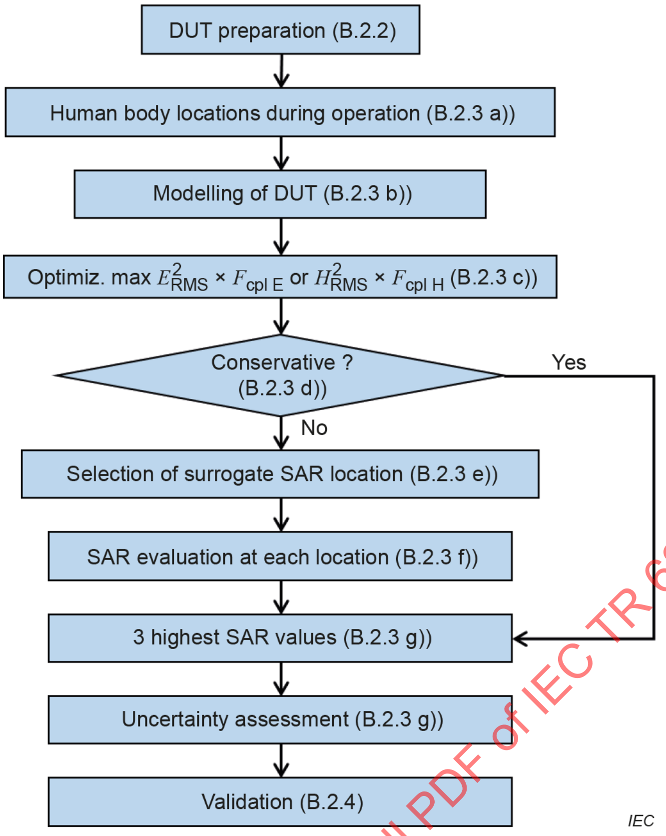

Figure B.1 – Flowchart for the SAR assessment procedure between 30 MHz to 6 GHz

B.2.2 Preparation of the device under test

The transmitted power of each antenna element and the frequency are controlled by the software provided by the manufacturer. The software is able to excite all power levels, frequency configurations, and phase configurations between the elements that can be excited during actual operation.

B.2.3 Transmitter SAR assessment procedure

The assessment includes the following steps:

a) determination of the assessment volume that includes all locations in which a human body part could be present during operation of the transmitter,

b) generation of a computational transmitter model that is validated according to IEC/IEEE 62704-1:2017 [18] or IEC/IEEE 62704-4:2020 [19]. The model is validated to reproduce the field configurations under normal operational conditions of the transmitter. Constraints posed by the WPT system are appropriately considered in the modelling,

c) maximization of the incident $E^2_{RMS} \times F_{cpl\ E}$ and $H^2_{RMS} \times F_{cpl\ H}$ for each operational constellation by optimizing frequency, amplitude and phase according to the methods of Annex C of IEC/IEEE 63195-2:2022 [20] in the entire volume. $F_{cpl\ E}$ and $F_{cpl\ H}$ are the worst-case coupling factors for the corresponding beamwidth. Annex D provides guidance on how to derive $F_{cpl\ E}$ and $F_{cpl\ H}$ using computational methods,

NOTE $E^2_{RMS} \times F_{cpl\ E}$ and $H^2_{RMS} \times F_{cpl\ H}$ are conservative intermittent surrogates for the spatial SAR averaged over 1 g and 10 g, allowing for determination of the maximum SAR exposure in free space (see Annex A).

d) if it can be demonstrated that $E_{\mathrm{RMS}}^{2} \times F_{\mathrm{cpl\ E}}$ and $H_{\mathrm{RMS}}^{2} \times F_{\mathrm{cpl\ H}}$ are conservative and that all values are within the limits for demonstrating compliance, go to Step g), otherwise continue with Step e),

e) selection of all locations (i.e. surrogate SAR locations) that are within the uncertainty of the maximum value and are separated by more than λ,

f) SAR assessment at all locations of Step e) using computational or experimental methods,

g) select the three highest SAR assessment values including locations and assess their uncertainties.

B.2.4 Validation of the SAR assessment

The validation includes the following steps:

a) validation of the radiative WPT system features for mitigating exposures using information obtained from the system sensors (e.g., proximity sensors, receivers, etc.),

b) selection of the highest assessed SAR value found in Step g) of B.2.3, and perform the assessment applying the measurement techniques and procedures using the adult and child phantom as specified in B.3.2 of IEC 62232:2017 [12],

   The experimental SAR measurements performed in Step f) of B.2.3 do not have to be repeated.

c) if the distance is greater than 200 mm, multiply the SAR values obtained in Step b) with the correction factors described in Annex A,

d) the results of Step c) are compared to the results of Step g) of B.2.3. If the result is within the combined uncertainties of Step b) and Step g) of B.2.3 then the assessments are considered successfully validated. Otherwise, B.2.3 is repeated. Higher deviations can be encountered if back-scattering affects the transmitter. In these cases, an assessment strategy is developed to consider these effects.

B.3 Incident power density (PD) assessment for local exposure over 6 GHz

B.3.1 General

The following procedure applies the methods of IEC/IEEE 63195-1:2022 and IEC/IEEE 63195-2:2022 [20]. It is summarized by the flowcharts shown in Figure B.2. While the methods of IEC/IEEE 63195-1:2022 [2] and IEC/IEEE 63195-2:2022 [20] are only specified for distances up to 200 mm, they can be applied without modification at greater distances because at the upper distance limit of 200 mm, far-field-like exposure conditions can always be assumed for the frequency range for which the methods are specified.

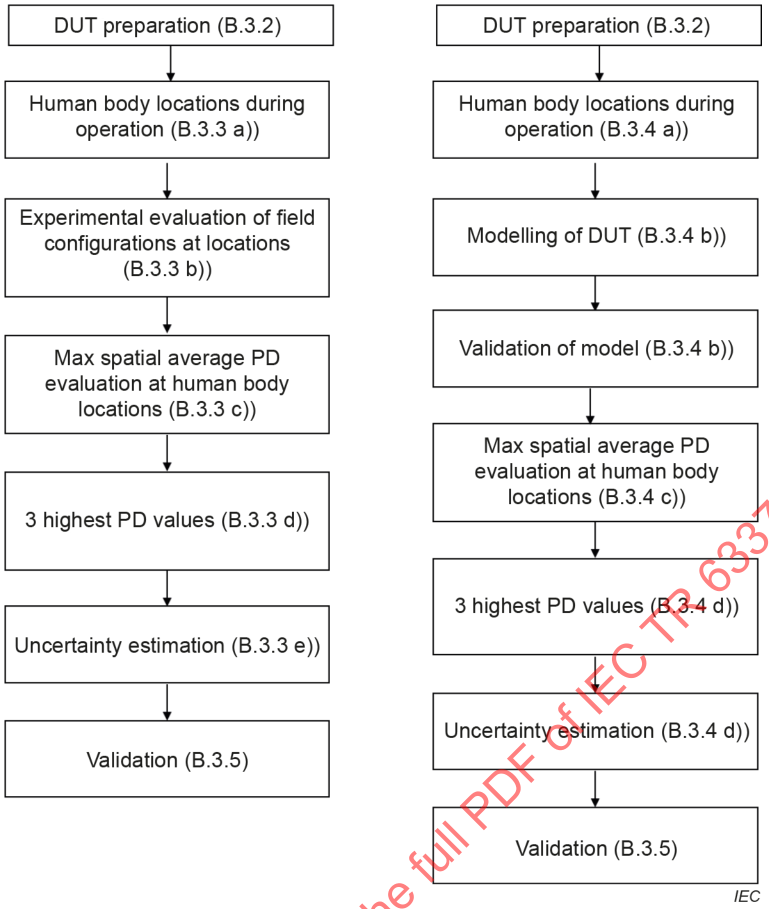

Figure B.2 – Description of PD assessment procedure between 6 GHz to 300 GHz

B.3.2 Preparation of the device under test

The transmitter power of each antenna element and the frequency are controlled by the software provided by the manufacturer. The software is able to excite all power levels, frequency configurations and phases between the elements that can be excited during actual operation.

B.3.3 PD assessment procedure – Experimental only

The assessment includes the following steps:

a) determination of the assessment volume that includes all locations where a human body part could be present during operation of the transmitter,

b) experimental assessment of a sufficiently large set of linearly independent configurations (amplitude and phase) required for field transformation and maximum PD assessment for all device configurations (frequency, amplitude, and phase) in the entire volume within which a human body part can be located during operation of the transmitter as specified in B.3.2 according to IEC/IEEE 63195-1:2022 [2] with known uncertainty,

c) perform the maximum spatially averaged PD assessment at any point in the volume according to IEC/IEEE 63195-1:2022 [2],

d) selection of all locations that are within the uncertainty of the maximum PD value,

e) report the highest PD values including location and uncertainties.

B.3.4 PD assessment procedure – Combined numerical and experimental methods

The assessment includes the following steps:

a) determination of the evaluation volume that includes all locations at which a human body part could be located during operation of the transmitter,

b) generation of a computational transmitter model that is validated according to IEC/IEEE 63195-2:2022 [20]. The model is validated to reproduce the field configurations under normal operational conditions of the transmitter. Constraints posed by the WPT system sensors need to be appropriately considered in the modelling,

c) perform the maximization of the spatial average PD according to IEC/IEEE 63195-2:2022 [20] at any point in the volume determined in Step a) using the validated numerical antenna models,

d) selection of all locations that are within the uncertainty of the maximum PD value,

e) report the highest PD values including location and uncertainties.

B.3.5 Validation of the assessment

The validation includes the following steps:

a) validation of the system features for mitigating exposure using information obtained from the WPT system sensors (e.g., proximity sensors, receivers, etc.) according to Annex C,

b) selection of configurations that include the maximum configuration found in B.3.3 or B.3.4,

c) the results of Step b) should be compared to Step d) of B.3.3 or B.3.4.

Annex C
(informative)

Description and validation of exposure mitigation techniques

C.1 General

This annex describes methods to validate exposure mitigation techniques for reducing the electromagnetic exposure of nearby persons when the radiative WPT system is in operation. The goal of an exposure mitigation technique is to maintain the electromagnetic exposure of nearby persons below the applicable exposure limit, as established in international exposure limits documents (e.g., ICNIRP [16]). This goal can be accomplished by controlling the output power of the antenna or steering the beam away from the person. Discussion in this document is limited to mitigation techniques directly controllable by the WPT system. Site-based and administration-based mitigation techniques, such as RF safety plans, signage, and positive access control, are outside the scope of this document.

Any exposure mitigation technique, if used, will meet the following general criteria:

a) the technique is not externally controlled;

b) the technique is not alterable by the user;

c) the method is fully documented in the test report. This includes whether a combination of mitigation techniques is used.

If the preceding criteria in a) to c) are not met, the exposure is assessed at the maximum output power level.

This annex applies to active methods of exposure mitigation. Passive methods, such as shielding, are considered part of the radiative WPT system.

C.2 Description of the technology and its implementation

Two categories of exposure mitigation (or a combination of both) can be used by WPT systems:

– Proximity sensors,

– Time-period power control.

Proximity sensors detect the presence of nearby persons and trigger a reduction in the radiated power so that their exposure is reduced. When the proximity sensor is triggered, the transmitter reduces the output power, or it applies beam steering to direct the radiation pattern away from the person, or both. Different proximity sensing techniques can be used, as described in, e.g., IEC 60947-5-2 [34]. These include capacitive sensing, optical or infrared sensing, ultrasonic methods, or information collected by receivers.

Time-period power control reduces the maximum output power of the antenna after a fixed period of time. The goal is to keep the exposure below the limit over the specified averaging time (e.g., 6 min).

C.3 Validation of proximity sensors

The purpose of this Clause C.3 is to validate that the proximity sensor is triggering at the intended distance and range. This procedure applies to the following conditions:

a) a single proximity sensor or multiple proximity sensors where the sensor responses are combined to provide a single unique and unconditional triggering,

b) single-step power reduction,

c) multiple-step power reduction

The steps of this validation process are as follows;

1) select the phantom type that well-represents the human body for the employed proximity sensor technology;
2) select the minimal phantom, e.g., child arm with hand;
3) use a manual procedure or an automated scanning system to approach the radiative WPT system to the closest distance at which the human can be exposed for different excitation configurations;
4) note all locations at which the proximity sensor is triggered and the power reduction per element;
5) compare the results with the information provided by the manufacturer. If the distance is less, stop the measurement or perform a comprehensive assessment covering the entire exposure volume.

NOTE An example test procedure for proximity sensors is described in IEC/IEEE 62209-1528:2020 [3].

C.4 Validation of time-period power control

The power control algorithm of SAR or PD can be validated directly by measuring the time-average exposure ($SAR_{\text{time-average}}$ or $PD_{\text{time-average}}$) directly at the location of maximum exposure (see Annex B).

NOTE An example test procedure for time-period power control is described in IEC/IEEE 62209-1528:2020 [3].

If the measurement results do not match the information provided by the manufacturer, perform a comprehensive assessment covering the entire exposure volume.

C.5 System level validation of the exposure mitigation techniques

Based on the knowledge of the exposure mitigation techniques, a number of tests are conducted to validate that the exposure mitigation techniques ensure compliance under all relevant conditions. At minimum, the following test is performed: however, it is possible that this will not be sufficient:

a) place the receiver at its minimum distance and in a second test at it maximum distance;

b) insert a body-part phantom, e.g., hand-arm phantom, from all sides (e.g., left, right, top, bottom) at the minimum distance from the radiative WPT source, at the mid-distance from radiative WPT source, and at 10 mm behind receiver;

   NOTE The range of body-part phantoms is realistic but conservative regarding the employed mitigation technique. The test range is comprehensive, e.g. small hand-arm and torso phantoms. The dependence of the movement speed might also need to be determined.

c) note all locations at which the proximity sensor is triggered and the power reduction per element;

d) at all pre-trigger locations determine compliance;

e) in the report, document the rationale as to why the specific system level validation of the exposure mitigation techniques was sufficient. In addition, document the maximum exposure if the exposure mitigation techniques fail and the associated risks of such a failure.

Annex D
(informative)

Computational methods

D.1 Methods and procedures

In general, full wave methods, which simulate electromagnetic fields that are solutions of the first and second of Maxwell's equations, i.e., Faraday's law and the Ampere/Maxwell law, need to be applied for dosimetric calculations in the frequency range within the scope of this document. Such methods are:

– Finite-difference time-domain method [35], [36],
– Finite element method [37],
– Method of moments, boundary element method [38], [39], [40],
– Finite-volume time-domain method [41],
– Hybrid methods combining two or more of the methods listed above.

The procedure on the computational methods for the assessment of the whole-body SAR and of the psSAR are given below:

a) full wave Maxwell's equations solver operating in the frequency-domain or time-domain;
b) modelling environment and mesh generator for the representation of the electrically relevant parts of the EUT and of nearby objects, such as a body phantom or an anatomical body model, for the rendering of its electric fields 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) interpolation of the frequency domain simulation results to specifiable points within the computational domain;
f) calculation of the dissipated power in the dielectrics;
g) superposition of the simulated E-vector and H-vector fields in the frequency domain of a specifiable number of simulation results using specifiable complex scaling factors, e.g., for the assessment of the beam steering of phased array antennas;
h) superposition of the far field of a specifiable number of simulation results using specifiable complex scaling factors including the assessment of the radiated power.

NOTE Quasi-static methods are not applicable.

D.2 Verification of the computational method

The computational software applied for the dosimetric assessment of WPT systems is verified for technically correct implementation. IEC/IEEE 62704-1:2017 [18], IEC/IEEE 62704-4:2020 [19], and IEC/IEEE 63195-2:2022 [20] specify appropriate benchmarks to verify all steps listed in Clause D.1 for finite-difference time-domain method and finite element method.

For other full-wave methods, such as the method of moments, the boundary element method, or the finite-volume method, no standardized benchmarks exist. If these methods are applied, they can be verified according to [42], or appropriate benchmarks should be developed to demonstrate their technically correct implementation.

D.3 Application of hybrid computational and experimental methods

Hybrid methods, which combine two or more computational methods or experimental and numerical methods, can be used to calculate or measure the incident fields of the WPT system independently from the exposed body or phantom, which can save computational time and resources for particular system designs. The following considerations should be taken into account when applying hybrid methods:

- Each of the computational methods and the interface between them need to be verified appropriately (Clause D.2);
- If the combined computational methods do not provide feedback to one another (e.g. if the simulation of dielectric load, such as the exposed body, does not provide any feedback to the simulation of the incident field), a demonstration example shows that this feedback can be neglected in the testing configuration;
- The uncertainty of the hybrid approach is quantified (Clause D.4).

D.4 Considerations for the assessment of the numerical uncertainty

D.4.1 General

The assessment of the numerical uncertainty is carried out according to the procedures specified in IEC/IEEE 62704-1:2017 [18], IEC/IEEE 62704-4:2020 [19], and IEC/IEEE 63195-2:2022 [20]. These are summarized as follows:

- Development and experimental verification of a numerical model of the EUT and assessment of its uncertainty, which includes both the modelling uncertainty and the experimental uncertainty of the measurement setup used for the validation;

  NOTE The validation of the numerical model of the EUT is only possible by comparison of its numerical results to appropriate measurements. This comparison can be carried out for a simplified dosimetric setup and a reduced number of testing configurations.

- Assessment of the numerical uncertainty of the testing configurations;
- Assessment of the combined and expanded uncertainty.

D.4.2 Parameters for the numerical uncertainty assessment

In the following, the most relevant parameters for the assessment of the numerical uncertainty are listed. Details on their quantification are given in IEC/IEEE 62704-1:2017 [18], IEC/IEEE 62704-4:2020 [19], and IEC/IEEE 63195-2:2022 [20]. These parameters can change depending on the applied numerical methods:

- Resolution of the mesh and representation of the geometrical details of the EUT and of the phantom;
- Convergence;
- Positioning uncertainties in the computational mesh (finite difference time-domain (FDTD) only);
- Spurious reflections from absorbing boundary conditions;
- Dimensions of the computational domain with respect to the spatial extension of the reactive fields of the EUT;
- Power budget;
- Dielectric parameters of the EUT materials;
- Maximization techniques (Annex C of IEC/IEEE 63195-2:2022 [20]);
- Particular considerations for hybrid methods.

Annex E
(informative)

Examples of exposure assessment

E.1 Example of the dosimetric assessment of a WPT transmitter operating at 900 MHz

E.1.1 Overview

This annex describes the dosimetric assessment of an indoor WPT transmitter operating in the 900 MHz range with a total conducted output power of less than 10 W. The assessment applies a combined numerical and experimental approach.

The WPT transmitter uses a linear array of eight patch antenna elements to direct the electromagnetic energy towards the receiver. The total length of the system is less than 1 m. An integrated proximity sensor system ensures that the closest exposure occurs at a distance of 300 mm from the antenna array. For smaller distances, the RF power is turned off.

The objective of the study was to determine the maximum exposure anywhere in space.

E.1.2 Method

E.1.2.1 Assessment

The following assessment was performed according to Annex B:

a) A single patch antenna element of the WPT transmitter was modelled using the finite-difference time-domain method. The model was validated according to IEC/IEEE 62704-1:2017 [18] by near-field measurements of the electric field without presence of a body or a phantom.

b) For modelling of the mutual coupling of the antenna elements and distortion due to back scattering from the phantom, all eight antenna elements were integrated into the numerical model. The results were validated experimentally;

c) For the model of the entire array, the phase configuration for maximum exposure was determined at distances of a) 400 mm, and b) 1 000 mm, by using optimization (B.2.3 of this document, and Annex C of IEC/IEEE 63195-2:2022 [20]);

d) The configuration of maximum exposure was experimentally validated using the adult and child box phantoms specified in IEC 62232 [12] at the location of maximum exposure (d = 400 mm, see Clause A.3);

e) The correction factors ($F_{\mathrm{cor}i}$) at this distance were determined using adult and child models of the virtual population [43] in different horizontal positions (centralized, and shifted by ±100 mm and ±200 mm);

f) The final assessment with the measured values multiplied by the $F_{\mathrm{cor}i}$ as the total uncertainty was kept below 30 %.

E.1.2.2 Numerical methods

All numerical assessments were performed using the FDTD method [36]. The antenna elements of the linear array were modelled in a rectilinear mesh with variable mesh spacing. The psSAR and whole-body SAR was calculated according to IEC/IEEE 62704-1:2017 [18] in the adult and child base-station phantoms specified in IEC 62232 [12]. For comparison with the results in the phantom, the anatomical models of an adult and a child were selected from the virtual population [43].

E.1.2.3 Measurements

The measurements of the fields of the antenna array were carried out with a robot-based dosimetric measurement system, with a free-space E-field probe for the frequency range from 30 MHz to 6 GHz, and a dynamic range of 2 V/m to > 1 000 V/m, to validate the numerical model and the worst-case configuration. A vector network analyser was used to evaluate the input reflection coefficient of each antenna element over a frequency range from 800 MHz to 1 GHz.

The dosimetric assessment was carried out with the same measurement system and a dosimetric probe with a frequency range from 700 MHz to 6 GHz. 1 g psSAR and whole-body SAR were assessed using the base-station phantoms specified in IEC 62232:2017 [12]. The entire volume was scanned using the fast volume scan plus a zoom scan at location of maximum exposure.

E.1.3 Model development and validation

The antenna elements were modelled using the original CAD data. The fine mechanical and geometrical details of the model required minimum mesh steps in the sub-millimetre range. The coaxial feed of the antenna elements is integrated in the models. Feeding network and phase shifters did not need to be integrated as these can be considered in the numerical model by appropriately changing amplitudes and phases of the sources in the modelled coaxial feeds. In a first step, a single antenna element was modelled and validated experimentally by measurements of the E-field distribution, as simulated and measured on a surface of 800 mm × 1 300 mm. The orientation of the surface was aligned with the main axis of the WPT system, and perpendicular to the antenna patches corresponding to the cross section shown in Figure E.1. The minimum measurement distance was 25 mm. The input reflection coefficient of the antenna element was compared to measurement data as well. In a second step, the entire array was modelled in the simulation because of the mutual coupling of the antenna elements. The antennas were fed using a coaxial source at their feed points. The feeding network was not included in the model.

Using the numerical antenna model, the maximum exposure was determined by optimizing the phase configuration of the antenna elements (per B.2.3 of this document and Annex C of IEC/IEEE 63195-2:2022 [20]). The incident field was maximized at two distances of: a) d = 400 mm, and b) d = 1 000 mm from the WPT transmitter. These phase configurations were experimentally validated by comparing measured and simulated E-field distributions.

A final validation of numerical and experimental results for maximized exposure was carried out according to 7.3.4 of IEC/IEEE 62704-1:2017 [18]. Both free-space measurements and dosimetric measurements in the base-station phantoms were compared and found to be within the mutual uncertainty of the experimental and numerical methods. In conclusion, the model of the WPT transmitter is sufficiently accurate for the dosimetric evaluations.

E.1.4 Dosimetric assessment of the anatomical models

The 1 g psSAR, the 10 g psSAR for the head and torso and for the limbs, as well as the whole-body SAR were determined in an adult and a child model of the virtual population [43]. The anatomical models were placed at the distances of maximum exposure of 400 mm and 1 000 mm. Figure E.1 shows the exposure of the child anatomical model from the E-field of the WPT transmitter. For the assessment of the variability of the psSAR and the whole-body SAR, the anatomical models were shifted horizontally by ±100 mm and ±200 mm with respect to their central position. Moreover horizontal and vertical polarization were evaluated by rotating the models.

For comparison, the adult and child base-station phantoms of IEC 62232:2017 [12] were evaluated dosimetrically for the same configurations. The dosimetric results were applied to derive correction factors as the ratio of the results of the anatomical models to those of the base station phantoms for children and adults. The respective maxima of all anatomical models and positions were compared to those in Table A.1.