



BSI Standards Publication

Case studies supporting IEC 62232 — Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure

National foreword

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TECHNICAL REPORT



Case studies supporting IEC 62232 – Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CASE STUDIES SUPPORTING IEC 62232 – DETERMINATION OF RF FIELD STRENGTH, POWER DENSITY AND SAR IN THE VICINITY OF RADIOCOMMUNICATION BASE STATIONS FOR THE PURPOSE OF EVALUATING HUMAN EXPOSURE

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IEC TR 62669, which is a Technical Report, has been prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure.

This second edition cancels and replaces the first edition published in 2011. This edition constitutes a technical revision.

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

Enquiry draft	Report on voting
106/473/DTR	106/482A/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

When referring to subdivisions of IEC 62232:2017, the number of the subdivision is followed by "(IEC 62232:2017)" in order to differentiate from subdivisions of the current document. For example:

- "defined in 6.4 (IEC 62232:2017)" should be read as "defined in 6.4 of IEC 62232:2017";
- "see 8.2" should be read as "see 8.2 of IEC TR 62669:2019".

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This document contains a series of case studies for the evaluation of electromagnetic (EM) sources transmitting in the frequency range 110 MHz to 100 GHz (including consideration of ambient sources from 100 kHz to 300 GHz) to support the methods specified in IEC 62232:2017.

Case studies presented in this document have been chosen to illustrate typical RF exposure assessments for the most common types of base stations (BS) deployed in mobile and wireless networks, such as small cells, street cells, macro base stations, and parabolic dish antennas used for wireless transmission or mobile backhaul.

The methodologies and approaches described in this document can be useful for the assessment of early 5G products and networks. Clause 13 is dedicated to the introduction, rationale and guiding principles for the implementation of RF exposure assessment using the actual maximum transmitted power or EIRP. While this approach is applicable to any type of BS, it is particularly important for BS using massive MIMO, which are intended to be introduced more predominantly in 5G networks. Multiple examples of case studies with BS using massive MIMO are provided in Clause 13 to Clause 16.

This document is informative. Each use case is described in the main body of the document and includes “lessons learned” and recommendations for improving IEC 62232:2017. More details, rationale and examples of reports are included in annexes.

CASE STUDIES SUPPORTING IEC 62232 – DETERMINATION OF RF FIELD STRENGTH, POWER DENSITY AND SAR IN THE VICINITY OF RADIOCOMMUNICATION BASE STATIONS FOR THE PURPOSE OF EVALUATING HUMAN EXPOSURE

1 Scope

This document, which is a Technical Report, presents a series of case studies in which electromagnetic (EM) fields are evaluated in accordance with IEC 62232:2017. The case studies presented in this document involve intentionally radiating base stations (BS). The BS transmit on one or more antennas using one or more frequencies in the range 110 MHz to 100 GHz and RF exposure assessments take into account the contribution of ambient sources at least in the 100 kHz to 300 GHz frequency range.

Each case study has been chosen to illustrate a typical BS evaluation scenario and employs the methods detailed in IEC 62232:2017. The case studies are provided for guidance only and are not a substitute for a thorough understanding of the requirements of IEC 62232:2017. Based on the lessons learned from each case study, recommendations about RF assessment topics to be considered in the next revision of IEC 62232 are proposed. The methodologies and approaches described in this document are useful for the assessment of early 5G products introduced for consumer trials or deployments.

This document provides background and rationale for applying a compliance approach based on the actual maximum transmitted power or EIRP. Guidance for collecting and analysing information about the transmitted power of a base station and evaluating its actual maximum RF exposure based on modelling studies or measurement studies on operational sites (in networks, sub-networks or field trials) is also presented.

2 Normative references

IEC 62232:2017, *Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure*

IEC 62479, *Assessment of the compliance of low-power electronic and electrical equipment with the basic restrictions related to human exposure to electromagnetic fields (10 MHz to 300 GHz)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62232:2017 and the following apply.

NOTE The additional terms and definitions given below will be added in the next edition of IEC 62232.

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**actual maximum**

<value of transmitted power or EIRP or exposure or RF compliance boundary> value reached during operations at a given percentile of the cumulative distribution function (CDF) of a statistical evaluation taking into account the averaging time t_{avg} and the variation of the BS load for the whole duration of the statistical evaluation

3.2**averaging time**

t_{avg}

appropriate time over which exposure is averaged for purposes of determining compliance

3.3**broadcast control channel****BCCH**

logical broadcast channel used by the base station in a GSM network to send information about the identity of the network

3.4**cumulative distribution function****CDF**

<of a real-valued random variable X evaluated at x > probability that X will take a value less than or equal to x

3.5**drive test**

series of measurements performed for assessing the coverage, capacity and quality of service of a base station or BS cluster

3.6**high speed downlink packet access****HSDPA**

enhanced mobile communications protocol, which allows UMTS networks to have higher data speeds and capacity

3.7**massive multiple-input, multiple-output****massive MIMO****mMIMO**

method used for multiplying the capacity of a radio link in a multicarrier cellular network in which a BS j is equipped with $M_j \gg 1$ antennas and communicates with K_j single-antenna UEs simultaneously on each time/frequency sample, with antenna-UE ratio $M_j/K_j > 1$

Note 1 to entry: Each BS operates individually and processes its signals using linear receive combining and linear transmit precoding (from [1]¹).

3.8**maximum transmitted power**

P_{TXM}

maximum total power transmitted by a base station under test measured during the transmitter ON period

¹ Numbers in square brackets refer to the Bibliography.

3.9 **new radio** **NR**

name used by 3rd Generation Partnership Project (3GPP) for the specification of 5G mobile networks

Note 1 to entry: See, for example, 3GPP 38.104 [2] for the specification of NR base stations.

3.10 **network manager** **NM**

system providing a package of end-user functions with the responsibility for the management of a network, mainly as supported by the element managers but also involving direct access to the network elements in a mobile network

[SOURCE: 3GPP TS 21.905 [3]]

3.11 **physical broadcast channel** **PBCH**

transmission channel that is used to transfer information to all mobile devices that are operating in a radio coverage area

Note 1 to entry: See 3GPP 36.211 [4] for LTE and 3GPP 38.211 [5] for NR.

3.12 **physical downlink control channel** **PDCCH**

channel that carries scheduling assignments and other control information

Note 1 to entry: See 3GPP 36.211 [4] for LTE and 3GPP 38.211 [5] for NR.

3.13 **physical downlink shared channel** **PDSCH**

downlink data channel for users

Note 1 to entry: See 3GPP 36.211 [4] for LTE and 3GPP 38.211 [5] for NR.

3.14 **physical resource block** **PRB**

<LTE> seven consecutive OFDM symbols in the time domain and 12 consecutive subcarriers in the frequency domain

Note 1 to entry: A physical resource block thus consists of 7×12 resource elements, corresponding to one slot in the time domain and 180 kHz in the frequency domain.

Note 2 to entry: In 5G NR, different number of symbols and subcarriers are possible. (from 3GPP 38.211 [5]).

3.15 **power combination factor**

multiplication factor that is applied to the power reduction factor in case of combination of multiple independent signals

3.16 **power reduction factor**

multiplication factor that is applied to the time-averaged maximum transmitted power in order to obtain its actual maximum value from its CDF

Note 1 to entry: The power reduction factor can also be applied to EIRP; see Equation (3) in 13.1.3.

3.17

rated maximum

<value of transmitted power or EIRP> value as declared by the manufacturer

3.18

resource block

RB

<LTE and 5G-NR> series of $N = 12$ consecutive subcarriers in the frequency domain

[SOURCE: 3GPP TS 36.211 [4] and 3GPP TS 38.211 [5]]

3.19

technology duty cycle factor

TDC

multiplication factor that is applied to the maximum transmitted power to get the time-averaged transmitted power at full load considering the time slots reserved for reception in Time Division Duplex (TDD) systems

Note 1 to entry: For Frequency Division Duplex (FDD) systems, the technology duty cycle is 1.

3.20

time-averaged

<value of transmitted power or EIRP> value taking into account the technology duty cycle factor of the signal and the averaging time t_{avg}

3.21

transmitted power

P_{TX}

total power transmitted by a base station under test during the transmitter ON period assessed either at the antenna input port(s) for passive antennas or as the total radiated power for base stations with built-in antennas

3.22

urban macro

UMa

BS configuration used for mobile network channel model simulations according to 3GPP TS 36.873 [6] and 3GPP TS 38.901 [7], where the BS antenna is installed at a height of 25 m corresponding to rooftops

3.23

urban micro

UMi

BS configuration used for mobile network channel model simulations according to 3GPP TS 36.873 [6] and 3GPP TS 38.901 [7], where the BS antenna is installed at a height of 10 m corresponding to poles

3.24

user equipment

UE

device used directly by an end-user to communicate in a mobile network

3.25

voice over LTE

VoLTE

high-speed mobile communication technology for mobile phones and data terminals with specific profiles for control and media planes to deliver voice service using LTE

4 Symbols and abbreviations

4.1 Physical quantities

The internationally accepted SI units are used throughout this document.

Symbol	Quantity	Unit	Dimensions
B	Magnetic flux density	tesla	$T, V s m^{-2}$
E	Electric field strength	volt per metre	$V m^{-1}$
f	Frequency	hertz	s^{-1}
H	Magnetic field strength	ampere per metre	$A m^{-1}$
J	Current density	ampere per square metre	$A m^{-2}$
λ	Wavelength	metre	m
S	Power density	watts per square metre	$W m^{-2}$

NOTE 1 In this document, temperature is quantified in degrees Celsius, as defined by: $T (^{\circ}C) = T (K) - 273,16$.

4.2 Constants

Symbol	Physical constant	Magnitude
c	Speed of light in vacuum	$2,997\ 9 \times 10^8\ m\ s^{-1}$
η_0	Impedance of free space	$376,730\ 3\ \Omega$ (approximately $120\pi\ \Omega$)
ϵ_0	Permittivity of free space	$8,854\ 188 \times 10^{-12}\ F\ m^{-1}$
μ_0	Permeability of free space	$4\pi \times 10^{-7}\ H\ m^{-1}$

4.3 Abbreviated terms

BS	base station
CDF	cumulative distribution function
DL	downlink
E -field	electric field strength
EBB	eigen-based beamforming or eigen-beamforming or eigen value based beamforming
eMBB	enhanced mobile broadband
EIRP	equivalent isotropic radiated power or equivalent isotropically radiated power
EM	electromagnetic
EMF	electromagnetic fields
ER	exposure ratio
EUT	equipment under test
FCC	Federal Communications Commission
FDD	frequency division duplex
FTP	file transfer protocol
FM	frequency modulation
2G/3G/4G/5G	generations of mobile technology
GOB	grid of beam
GSM	Global System for Mobile communications (originally <i>Groupe Spécial Mobile</i>)
GP	general public (or general population)

HPBW	half-power beamwidth
HSDPA	high speed downlink packet access
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IP	Internet Protocol
ISM	industrial, scientific and medical
LoS	line of sight
LTE	Long Term Evolution
MIMO	multiple-input, multiple-output
mMIMO	massive multiple-input, multiple-output
NM	network manager
NR	new radio
OFDM	orthogonal frequency division multiplexing
PA	power amplifier
PBCH	physical broadcast channel
PDCCH	physical downlink control channel
PDSCH	physical downlink shared channel
PRB	physical resource block
PTX	transmitted power
RB	resource block
Rx	receiving
RAT	radio access technology
RF	radio frequency
RS	reference signal
SA	spectrum analyser
SAR	specific absorption rate
SCF	Small Cell Forum
TDC	technology duty cycle
TDD	time division duplex
TER	total exposure ratio
Tx	transmitted
UL	uplink
UMa	urban macro
UMi	urban micro
UMTS	Universal Mobile Telecommunications System
VoLTE	voice over LTE
WCDMA	wideband code division multiple access

5 Overview of case studies

Case studies presented in this document have been chosen to illustrate typical RF exposure assessments of base stations deployed in mobile networks; these include small cells, street cells, macro base stations and wireless links incorporating parabolic dish antennas used for wireless transmission or backhaul.

The case studies address both measurements and computation techniques used for the three main applications of RF exposure evaluation specified in 5.3 (IEC 62232:2017).

- a) Product compliance: determination of RF compliance boundary information for a BS product before it is placed on the market.
- b) Product installation compliance: determination of the total RF exposure levels in accessible areas from a BS product and other relevant sources before the product is put into service.
- c) In-situ RF exposure assessment: measurement of RF exposure levels in the vicinity of a BS installation after the product has been installed and is operating.

The full list of case studies is provided in Table 1.

NOTE Although a number of case studies are based on ICNIRP exposure limits [8], other exposure limits may apply depending on where such equipment is intended to be approved for use. Methodologies used in this document are still applicable in the context of ICNIRP_PCD_2018_07_11 [9]. It is intended that analysis of any further change to ICNIRP Guidelines will be performed during the revision of IEC 62232.

Table 1 – Outline of RF exposure assessment case studies

Clause	Annex (incl. test reports)	Base station type	Evaluation type with IEC 62232:2017 reference	Evaluation method with IEC 62232:2017 reference
6	Annex A	Small cell (indoor local area BS)	Product compliance (6.1)	SAR measurements (B.3.2)
7	Annex B	Small cell (outdoor medium range BS)	Product compliance (6.1)	SAR measurement (B.3.2)
8	Annex C	Small cell	Product installation compliance (6.2)	Field strength computations (B.4)
9	Annex D	Small cell	In-situ RF exposure assessment (6.3)	Field strength measurements (B.3.1)
10	Annex E	Street cell	Product compliance (6.1)	SAR (B.3.2) and field strength (B.3.1) measurements
11	Annex F	Macro	In-situ RF exposure assessment (6.3)	Field strength measurements (B.3.1)
12	Annex G	Macro (inspection with drone)	In-situ RF exposure assessment (6.3)	Field strength measurements (B.3.1)
13	none	All types of BS	Compliance using the actual maximum transmitted power or EIRP	Field strength measurements (B.3), computations (B.4) and actual maximum (B.5)
14	Annex H	Macro (massive MIMO)	Product compliance (6.1)	Field strength computations (B.4)
15	Annex I	Macro and small cell (massive MIMO)	Product installation compliance (6.2)	Field strength computations (B.4)
16	Annex J	Small cell (massive MIMO)	Product installation compliance (6.2) and in-situ RF exposure assessment (6.3)	Field strength measurements (B.3) and computations (B.4)
17	Annex K	Wireless link using parabolic dish antenna	Product compliance (6.1)	Field strength computations (F.11)

6 Indoor small cell product compliance assessment using SAR measurements

6.1 General description

This case study describes a product compliance assessment of a local area BS product (small cell) utilizing two radios in a 3G and 4G mixed mode configuration. The assessments are performed using methodology specified in IEC 62232. The BS product considered operates in the 2,1 GHz and 2,6 GHz frequency bands. Each radio, denoted RF1 and RF2, is connected to two separate internal antennas with fixed beam pattern located on the rim of the product according to Figure 1.

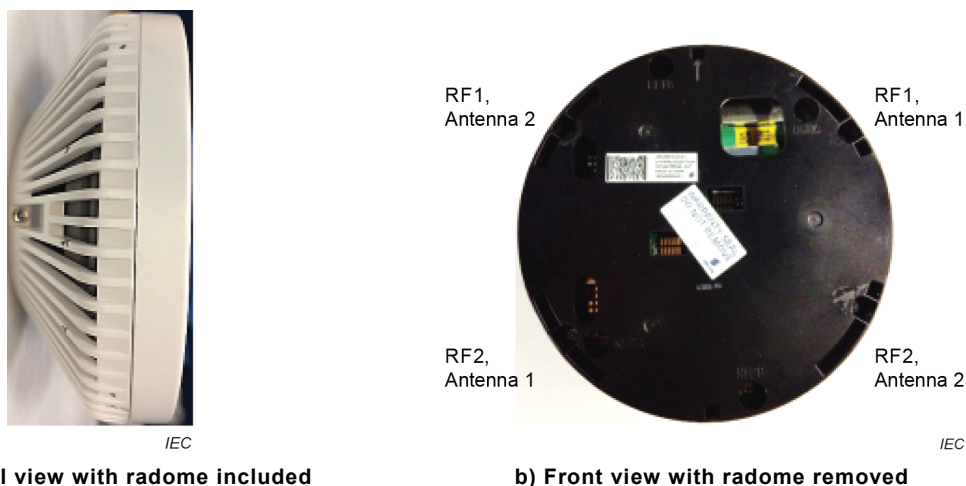


Figure 1 – Tested local area BS product with two radios denoted RF1 and RF2

The purpose of the assessment is to determine the RF compliance boundary beyond which the radio frequency exposure is below the ICNIRP general public and occupational basic restrictions provided in Table 2. The evaluation is based on localized 10 g maximum peak spatial-average SAR measurements.

Table 2 – ICNIRP RF exposure limits relevant for the product compliance assessment (from [8])

Basic restrictions (localized 10 g SAR)	
General public	Occupational
2 W/kg	10 W/kg

The technical details of the local area BS product can be found in Clause A.1.

Clause A.2 provides more details about the test report as required by IEC 62232.

6.2 Implementation of IEC 62232:2017

6.2.1 Evaluation process

This product compliance assessment follows the procedure as specified in 6.1 (IEC 62232:2017). Due to the transmitted power specified, the conformity assessment methods described in IEC 62479 are not applicable. Compliance boundary information is determined for a typical configuration of the BS product assuming free-space conditions.

The use of SAR measurements was selected, and the procedures described in 6.1.5.3 (IEC 62232:2017) were used. Using the guidelines of Figure 12 and 8.2.3 (IEC 62232:2017), it was found that only localized 10 g SAR measurements are required as the whole-body SAR exclusion in Table 5 (IEC 62232:2017) applies.

6.2.2 Methodology

For the equipment under test (EUT) a simple RF compliance boundary in the form of a circular cylinder was selected based on the guidelines in 6.1.4 (IEC 62232:2017). The RF compliance boundary is described in terms of the compliance distances in front of the EUT, behind the EUT and in the radial direction, according to Figure 2. Outside of this cylinder the RF exposure is below the exposure limits.

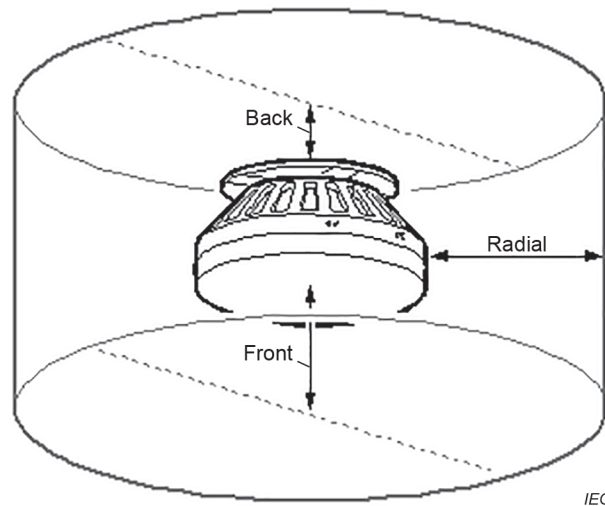


Figure 2 – Definition of cylindrical RF compliance boundary

A requirement of the compliance evaluation is to specify the set of conservative BS parameters for a BS under normal use; this requires a detailed analysis specific to the employed technologies. The EUT can be configured for both LTE and WCDMA (RF1) and LTE (RF2). As each radio is connected to two antennas, the combined exposure needs to be considered. A key requirement is to determine if the combined exposure shall be assessed assuming correlated or uncorrelated exposure.

The fields from RF1 and RF2 are always uncorrelated since disjoint frequency bands are used [10]. For WCDMA, it is possible to configure the EUT such that:

- a) different RF carriers are mapped to different antennas;
- b) a common precoder is used to map the same RF carrier to both antennas (but with different local oscillators, see below).

For the first case, the fields transmitted by the two antennas will be uncorrelated since disjoint frequency bands are used [10]. For the second case, the use of the different local oscillators implies that the fields will not add coherently. The antennas, evenly spaced along the sides of the EUT, have also been designed to transmit in different directions. Consequently, the exposure assessments for WCDMA have been performed with the assumption that the fields emitted from the antennas are uncorrelated.

For LTE, the EUT makes use of Transmission Mode 3, which implies that open-loop codebook-based precoding is used if more than one layer is transmitted, and that transmit-diversity is used in the case of rank-one transmission [11]. Transmit-diversity for two antenna ports is based on Space-Frequency Block Coding which implies that two consecutive modulation symbols are mapped on frequency-adjacent resource elements on the first antenna port. On the second antenna port, the frequency-swapped and transformed symbols are mapped to the corresponding resource elements. Since the signals associated with the two antennas are different for each subcarrier, the fields transmitted by the two antennas will be uncorrelated [10]. In addition, for open-loop codebook-based precoding, the signals on the two antenna ports will in general be different resulting in uncorrelated exposure. Thus, for LTE, the exposure assessments have also been performed with the assumption that the fields emitted from the antennas are uncorrelated.

To obtain the total exposure in the front direction, a simple conservative approach was used where the maximum exposure ratios per antenna and channel configuration were summed. Since the antennas are evenly distributed along the sides of the EUT, the exposure to the sides was taken as the maximum exposure for the individual configurations.

In this product compliance assessment, results were obtained for the maximum transmitted power, which is the rated maximum transmitted power plus the power tolerance (provided by the client) related to electronic component dispersion during manufacturing and operational environmental conditions (temperature). This is most likely very conservative as effects of BS utilization and power control mechanisms are neglected.

6.2.3 Reporting

The test report is provided in Clause A.2. The measurement uncertainty was determined according to 6.1.6 and Clause 9 (IEC 62232:2017), and the results, including the SAR values, were reported according to 6.1.7 and Clause 10 (IEC 62232:2017).

6.3 Technical outcome

The RF compliance boundary dimensions obtained from the assessments are provided in Table 3. Since all distances are zero, no compliance boundaries exist, and the product is touch-compliant for both general public and occupational exposure conditions.

Table 3 – Dimensions of the cylindrical-shaped RF compliance boundary for general public (GP) and occupational (O) exposure

Mode and transmitted power for the EUT				Dimensions of the cylindrical-shaped RF compliance boundary (m)					
				Distance in front of EUT		Distance in radial direction		Distance behind EUT	
3GPP band	Standard	Rated max. transmitted power from the EUT	Maximum transmitted power	GP	O	GP	O	GP	O
B1 and B7	WCDMA/LTE	4 × 50 mW	4 × 79 mW	0	0	0	0	0	0

6.4 Lessons learned

For accurate compliance assessment results, it is critical that the set of conservative BS parameters is properly described. For BS products where the combined exposure from several sources are to be considered, it is important to determine if the corresponding fields can add coherently and whether the combining shall be performed assuming correlated or uncorrelated exposure [10]. Factors such as signal characteristics, antenna polarization and antenna placement need to be considered.

Based on a trade-off between exposure assessment simplicity and accuracy, the test laboratory can choose to adopt more or less conservative combining methods. More specific guidelines should be considered in the next edition of IEC 62232.

For the next edition of IEC 62232, it should also be considered to add near-field power density assessment methods for small cell BS operating at millimetre range frequencies leveraging the information provided in IEC TR 63170 [12] and the concurrent development of standards by IEC TC 106 specifying computation and measurement methods.

7 Outdoor small cell product compliance assessment using SAR measurements

7.1 General description

This case study describes a product compliance assessment for an outdoor medium range BS product (see Table B.1). The product, called EUT, consists of a small and low-power remote radio equipment, as shown on Figure 3. The EUT transmitted power is less than 1 W per port (i.e. total less than 4 W) and EUT typically provides a localized coverage area from an elevated location.

The antenna used in the EUT has vertical/horizontal polarization in common. Therefore, two branches of multiple-input, multiple-output (MIMO) can be treated in one antenna and two antennas are necessary to operate in 4×4 MIMO mode.

This type of small cell is typically deployed for localized coverage area. In this case, the compliance distance is expected to be within 1 m, which is appropriate for SAR measurements.



Figure 3 – Small remote radio equipment at 3,5 GHz (EUT antenna)

The assessment is performed using methodology specified in 6.1 and B.3.2 (IEC 62232:2017). The SAR measurements were performed in an anechoic chamber and the measurement system comprises conventional SAR probes, data acquisition electronics and positioner. An estimation technique based on uniform exponential decay [13] was used in addition to IEC 62232:2017 to reduce the measurement time for evaluating localized 10 g SAR and whole-body SAR.

Localized 10 g SAR and whole-body SAR obtained using the SAR measurement system described above were compared to the basic restrictions in the international guidelines provided by ICNIRP [8].

7.2 Implementation of IEC 62232:2017

7.2.1 Evaluation process

This product compliance assessment follows the procedure as specified in 6.1 (IEC 62232:2017). The use of SAR measurements was selected, and the procedures described in 6.1.5.3 and B.3.2 (IEC 62232:2017) were used. Using the guidelines of Figure 12 and 8.2.3 (IEC 62232:2017), it was found that localized 10 g SAR and whole-body SAR measurements are required as the whole-body SAR exclusion in Table 5 (IEC 62232:2017) does not apply.

SAR measurements were performed using EUT antenna with external RF source. RF power was supplied to the antennas using vector signal generators and RF amplifiers. To derive localized 10 g SAR and whole-body SAR, an isotropic electric field probe and positioner were used.

The exposure limits for this evaluation are referred to basic restrictions of the ICNIRP guidelines [8]. For general public exposure, localized 10 g SAR (head and trunk) and whole-body averaged SAR limits are 2 W/kg and 0,08 W/kg, respectively.

7.2.2 Methodology

For the EUT, a simple RF compliance boundary in the form of a box was selected based on the guidelines in 6.1.4 (IEC 62232:2017). In this case study, the distance to the compliance boundary in the main beam direction, D_f , was evaluated. The SAR measurement for products was performed in a laboratory. An isotropic electric field probe scanned the inside of the phantom which is specified in B.3.2.2.1 (IEC 62232:2017) as "large box-shaped phantom". The phantom was filled with tissue-equivalent liquid. Two-dimensional SAR distribution near the bottom surface of the phantom was measured and post-processing derived localized 10 g SAR and whole-body SAR.

7.2.3 Reporting

The test results are provided in Clause B.4 for two antenna configurations: single antenna and MIMO. The measurement uncertainty is determined according to 6.1.6 and Clause 9 (IEC 62232:2017), and the results are reported according to 6.1.7 and Clause 10 (IEC 62232:2017).

7.3 Technical outcome

The technical outcome is the localized 10 g SAR and whole-body SAR as a function of distance between the antenna and the phantom. The distance to the box-shaped compliance boundary in the main beam direction, D_f , was less than 0,2 m in this case study.

7.4 Lessons learned

Both single antenna and MIMO configurations provide similar results for localized 10 g SAR. In this case study, SAR was measured when a signal with a downlink occupation time rate of 100 % was generated by a signal generator. On the other hand, the time occupancy rate of the downlink signal radiated from the actual TDD-LTE base station fluctuates according to some parameters, for example the uplink-downlink configuration, and it is less than 100 %. Therefore, in order to obtain the SAR in practical operations, a more detailed procedure with the time occupancy rate to measure the SAR of base station antennas for TDD systems should be investigated considering [13] and added in the next edition of IEC 62232.

8 Small cell product installation compliance assessment using simplified installation criteria

8.1 General description

Small cells are low-power BS that provide mobile and internet services within localized areas [14]. Small cells typically have a range from ten metres to several hundred metres in the current 3G and 4G networks. A report [15] estimated that about ten medium range small cells would be deployed per macro base station site to improve capacity and coverage in urban areas. Small cells are also expected to be widely deployed with 5G.

The 3GPP is the international standardization body developing specifications for telecommunications systems such as 2G, 3G and 4G. The 3GPP has specified four base station (BS) classes based on transmitted power in 3GPP TS 25.104 [16] and 3GPP TS 36.104 [17] (see Annex C). Small cells are generally considered to cover medium range BS, local area BS and home BS classes. A report from the Small Cell Forum (SCF) and the GSMA [18] provided typical examples of small cell product configurations (see Table 4 below) and their EIRP range that is one of the key criteria for the implementation of 6.2.4 (IEC 62232:2017). The case studies presented in Clause 8 and Annex C are also extracted from [18].

Table 4 – Typical examples of small cell configurations (from [18])

3GPP BS class	Configuration	Total rated maximum Tx power over all bands	Gain range	Rated maximum EIRP range
Medium range BS	2 bands	20 W	7 dBi to 13 dBi	100 W to 400 W
	1 band	10 W	7 dBi to 13 dBi	50 W to 200 W
Local area BS	5 bands	2,5 W	2 dBi to 5 dBi	4 W to 8 W
	1 band	0,5 W	2 dBi to 5 dBi	0,8 W to 1,6 W
Home BS	5 bands	100 mW	0 dBi to 3 dBi	0,1 W to 0,2 W
	1 band	20 mW	0 dBi to 3 dBi	0,02 W to 0,04 W

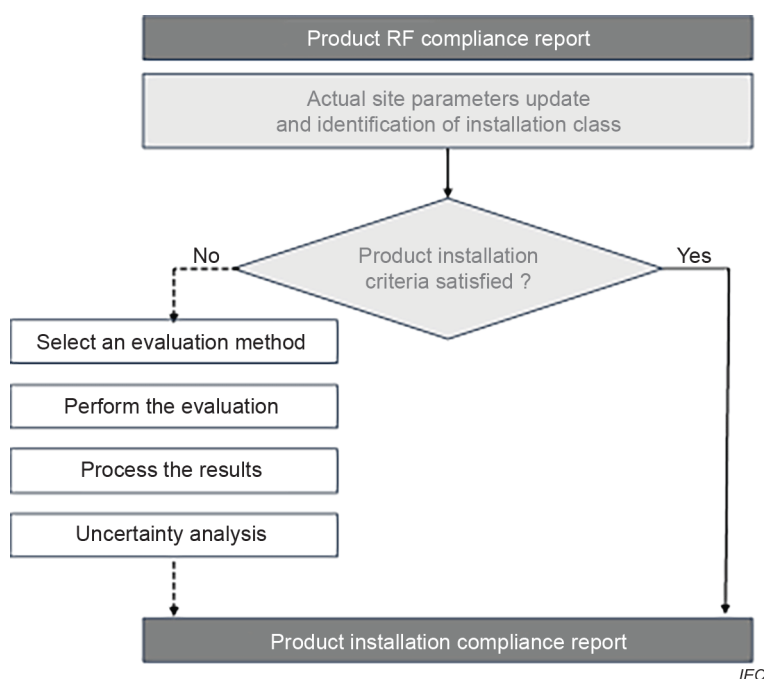
8.2 Implementation of IEC 62232:2017

8.2.1 Evaluation process

The purpose of this case study is to demonstrate how to implement the simplified product installation evaluation process specified in 6.2.4 (IEC 62232:2017) and the product installation classes specified in Table 4 (IEC 62232:2017) in relation with ICNIRP exposure limit guidelines.

NOTE Other processes can apply depending on where such equipment is intended to be installed and approved for use.

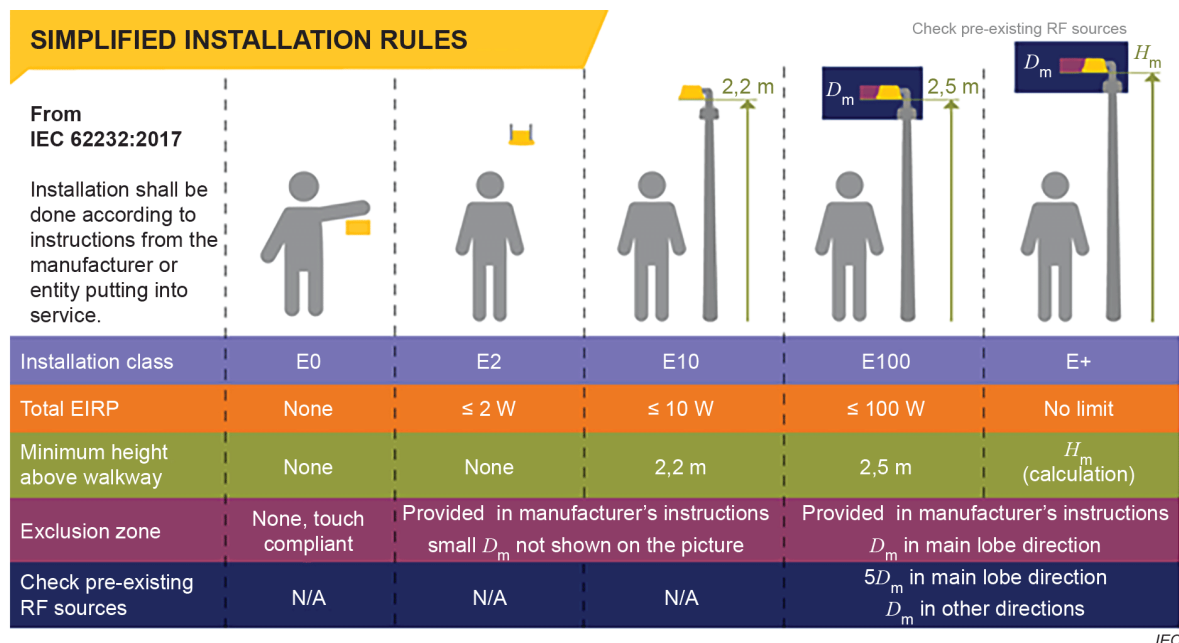
The process is derived from IEC 62232:2017 and represented in Figure 4. Once the BS product RF compliance boundary has been assessed based on 6.1 (IEC 62232:2017), the entity putting the BS into service can use the criteria specified in Table 2 (IEC 62232:2017) for assessing compliance without the requirement to perform a field evaluation based on measurements or calculations. This process is straightforward and can be implemented for groups of BS having the same characteristics and installation criteria.



[SOURCE: Small Cell Forum and GSMA [18]]

Figure 4 – Simplified process for product installation compliance applicable to small cells

Figure 5 outlines the key parameters of the installation classes specified in Table 2 (IEC 62232:2017).



[SOURCE: Small Cells Forum and GSMA [19]]

Figure 5 – Overview of BS installation classes for simplified RF exposure assessment of small cells

8.2.2 Methodology

The principle is that the entity putting the product into service provides a minimum number of parameters that are required to demonstrate product installation compliance according to 6.2 (IEC 62232:2017). These include:

- transmitting frequency;
- transmitted power;
- gain;
- installation height;
- product compliance distance according to 6.1 (IEC 62232:2017).

For equipment collocated on the same site, the total EIRP is considered. For example, four products with 25 W EIRP can be deployed on the same site using installation class E100 criteria.

In the evaluation of EIRP (from transmitted power and gain), a tolerance is applied to take into account the dispersion of electronics components, temperature range and manufacturing process. If this information is not available, a default value of 1 dB can be considered realistically foreseeable.

8.2.3 Reporting

The results are reported according to 6.2.9 and Clause 10 (IEC 62232:2017).

8.3 Technical outcome

Five case studies representing E0, E2, E10, E100 and E+ installation classes are provided in Annex C including all the technical details and figures representing typical installation.

8.4 Lessons learned

The simplified evaluation process specified in 6.2.4 (IEC 62232:2017) ensures that low-power equipment can be installed on a large scale using a minimal number of product and product installation parameters. In-situ measurement campaigns performed on more than 114 sites (see Clause 9) confirm that the level of exposure remains very low compared to exposure limits.

The criteria specified in Table 2 (IEC 62232:2017) can be used in dialogue between the entity putting the product into service and the local or national authorities (if applicable). Therefore, it is important that the material in Table 2 (IEC 62232:2017) be self-contained and written in a language that is accurate from a scientific perspective and understandable by those who are not experts.

For the next edition of IEC 62232, it should also be considered to:

- a) add a flow chart for the implementation of simplified criteria (e.g. Figure 4) and simplify text for better understanding by a third party (e.g. in Table 2 (IEC 62232:2017));
- b) develop an extended table that is applicable to other exposure guidelines than ICNIRP;
- c) add a new installation class or classes relevant for 5G products as well as the scientific rationale available for exposure assessment;
- d) review E+ class criteria, in particular information about the main lobe direction, the number and EIRP range of pre-existing BS;
- e) address small cells using massive MIMO;
- f) add specific information about computation uncertainty.

9 Small cell site in-situ measurements

9.1 General description

This case study describes two in-situ RF exposure measurement campaigns, denoted Campaign A and Campaign B, performed in proximity to small cells using methodology specified in IEC 62232:2017. Each campaign includes specific refinements of the protocol.

The purpose of in-situ measurement campaigns is to determine if the RF exposure levels are in compliance with ICNIRP general public exposure reference levels [8] taking into account the ambient sources. They can also be used to derive RF exposure data for information purposes.

9.2 Implementation of IEC 62232:2017 for measurement Campaign A

9.2.1 Evaluation process

Multiple trials have been performed in France to evaluate the impact of small cells that are deployed to improve the capacity and coverage of the macro BS network.

Two trial clusters have been chosen in this study. These clusters cover typical installation configurations in terms of street furniture (also called street fixture) technologies, and frequency bands used.

Both French trials have been performed in urban areas on the operational 4G networks of two mobile operators. Notably, one of the trial clusters was situated in an area of high population density compared to the other (by a factor 10). Each cluster includes a few sites (4 or 5) installed on street furniture as shown on Figure 6. The antenna heights are between 2,9 m and 5 m.



Figure 6 – Illustration of small cells integration in street furniture

The procedure described in Figure 10 of 6.3 (IEC 62232:2017) was applied. After source determination and site analysis, the measurement metrics have been determined according to 7.2.3 (IEC 62232:2017).

Measurements have been performed by an accredited laboratory.

Complementary measurements, i.e. beyond the mandatory RF exposure assessment process, have also been performed to evaluate the impact of small cells performances. The main objective of these complementary measurements was to provide more comprehensive information to the public; for example, by showing that their total exposure involves contributions from both the BS and from their mobile device.

By bringing the antennas closer to users, it is reasonable to expect the exposure induced by mobile devices to also reduce due to reduction in the transmitted power of the mobile phone. By increasing the available throughput for users, small cells are also expected to reduce duration of exposure for a given scenario. Additional measurements have been performed using handheld drive test devices to address questions about the impact of small cells on the exposure of the mobile phone user to support communication and dialogue with stakeholders. Walk tests have been performed in outdoor accessible zones within the 100 m radius zones around small cells. The handheld drive test device was set up to repeatedly upload 100 MB files and make 30-s voice calls when VoLTE was available.

9.2.2 Methodology

9.2.2.1 General

The source determination is based on visual inspection and consultation of an available database [20]. The measurement area has been chosen as the 100 m radius zone around the small cell installation. The assessment metric used in this measurement area is electric field strength.

Given the objective is to provide a detailed evaluation of RF exposure levels, a Case B evaluation has been performed. The Case B has been preceded by a Case A evaluation as recommended in 6.3.2.1 (IEC 62232:2017).

9.2.2.2 Case A (broadband evaluation)

The Case A evaluation has been performed by using a broadband instrument as specified in 6.3.2.2 (IEC 62232:2017). The process began by performing intermediate measurements at a height of 1,5 m above ground. To minimize perturbation by non-permanent and controlled sources, mobile devices (mobile phones, connected objects, etc.) were switched off when possible. To minimize the perturbation by a person holding the probe, a wooden tripod has been used to support broadband instrument during measurement. The intermediate points cover the entire 100 m radius zone and enable to identify the location of the maximum exposure. The intermediate measurement results are provided in the report.

The final measurement was performed at the location of maximum exposure with an average of 6 min or when the displayed value is stabilized for all three heights: 1,1 m, 1,5 m and 1,7 m.

9.2.2.3 Case B (comprehensive exposure evaluation)

The Case B measurements have been performed as specified in 6.3.2.3 (IEC 62232:2017) by using the *E*-field selective meter associated with three antennas covering 100 kHz to 30 MHz, 30 MHz to 470 MHz and 470 MHz to 6 GHz frequency ranges.

The detailed assessment is performed at the location of the maximum exposure identified during the Case A measurements. The measurement is averaged over 6 min or less when the displayed value stabilized for all three heights: 1,1 m, 1,5 m and 1,7 m. For each service, all the sources above 0,05 V/m are reported.

The extrapolation of the exposure to the network maximum traffic load has been performed for significant sources (i.e. above 0,3 V/m). For LTE signals, the method using a basic spectrum analyser has been used, see F.7.2.3 (IEC 62232:2017).

9.2.2.4 Consistency analysis

In addition to requirements imposed by IEC 62232:2017, an analysis of consistency between Case A result and Case B result before extrapolation process is performed when the Case A result is above 1 V/m. The analysis consists in checking that the difference between the two results is not too large. A difference of 20 % is considered as acceptable.

9.2.3 Reporting

The measurement uncertainty was determined according to Clause 9 (IEC 62232:2017), and the compliance was evaluated without considering measurement uncertainty. The reporting is performed according to 6.3.4 and Clause 10 (IEC 62232:2017).

The French report template has been used (see template in [21]). Complementary results are not part of the compliance test report.

Clause D.2 provides general results obtained from compliance measurements and field tests and provides one example of compliance test report following the requirements of Clause 10 (IEC 62232:2017).

9.3 Implementation of IEC 62232:2017 for measurement Campaign B

9.3.1 General description

Small cell sites are deployed to complement the existing mobile network infrastructure, especially in dense urban areas. A study involved conducting measurements to determine the RF exposure around small cell installations. The measurement Campaign B includes 98 sites located in South Africa (80), the Netherlands (16) and Italy (2).

The small cells surveyed for this project were selected from operator database information. Sites were classified in three groups: "Indoor", "Outdoor 2 m to 4 m" and "Outdoor > 4 m". As the title suggests, the "indoor" group (47) is comprised of installations where antennas are installed indoors; typically, a distributed antenna system, which is designed to provide localized coverage inside a building. Installations where antennas are mounted outdoors at a height of between 2 m and 4 m are classified as "Outdoor 2 m to 4 m" (30). A small cell installation at a bus stop is an example of a site in this group. "Outdoor > 4 m" (21) involves scenarios where the antenna is mounted outdoors, at a height of at least 4 m. A small cell installed on a lamp pole is an example of such an installation. Typical examples of sites measured during the survey are presented in Figure 7.



Figure 7 – Photographs of typical examples of the three small cell site groups

The measurements were performed based on 8.2 (IEC 62232:2017). As the objective was to provide a detailed evaluation of RF exposure levels, a Case B measurement was performed according to 6.3.2.3 (IEC 62232:2017). Despite a Case A measurement not being performed over the 100 kHz to 30 GHz frequency band, measurement results were captured and recorded for the 27 MHz to 3 GHz frequency range covered by the instrument described below.

For this specific study, the measured results at the time of the survey are reported. Extrapolation to maximum exposure as specified in B.5.3 (IEC 62232:2017) to maximum exposure was not performed.

9.3.2 Case B (comprehensive exposure evaluation)

The Case B in-situ measurements were performed according to 6.3.2.3 (IEC 62232:2017) using a spectrum analyser with isotropic *E*-field antenna covering 27 MHz to 3 GHz.

The technologies used on the sites surveyed have distinct frequency bands for downlink (from the BS to the UE) and uplink (from the UE to the BS). This Case B measurement focused on the downlink signal, i.e. the signal from the small cell site.

A specific test device used for mobile network drive tests was used to establish a download transmission from the small cell site being surveyed and to ensure that the download was active for the duration of the measurement survey. This test device was kept at some distance from the measurement equipment to minimize the effect on field strength measurements from uplink signals.

At each site, three publicly accessible positions were typically surveyed. These include a position of possible maximum exposure close to the site and two additional positions within 50 m of the small cell site.

During the measurements, the spectrum analyser and antenna was mounted on a wooden tripod. Measurement results were recorded at 1,1 m; 1,5 m and 1,7 m above ground to determine a spatial average. At each height, a measurement was performed for 60 s. The measurement

device "Safety Evaluation" mode was used, in order to report the exposure results integrated over pre-configured frequency bands.

The range of the measurement device is set at each position to a level as low as possible to ensure maximum sensitivity without saturating the spectrum analyser.

9.3.3 Reporting

The measurement uncertainty assessment was performed according to Clause 9 (IEC 62232:2017), and the results are reported without considering measurement uncertainty; see more details in D.3.5.

Clause D.3 provides an overview of the results obtained during this measurement Campaign B.

9.4 Lessons learned

The in-situ methods specified in 6.3 (IEC 62232:2017) have been successfully applied to large scale RF exposure measurement campaigns in the vicinity of small cells. The outcome of these campaigns can be used for compliance assessment and information purposes. In this objective, complementary field tests with test devices as illustrated in 9.2 are one solution to evaluate the impact of a technology on human exposure from a mobile device operating under real operational conditions.

Practical guidance for performing in-situ measurement campaigns on 5G small cell BS using massive MIMO should be considered in the next edition of IEC 62232.

10 Street cell product compliance assessment using SAR measurements and power density spatial averaging

10.1 General description

For small cell products with sufficiently low transmitted power, particularly indoor small cells, whole-body SAR testing is not required according to Table 5 of 8.2.3 (IEC 62232:2017), and only localized SAR assessments are needed. For small cell products with higher transmitted power, whole-body SAR measurements can be implemented but such measurements can be very time consuming. Instead, they can be replaced by power density spatial averaging according to B.3.1.4 (IEC 62232:2017). Similar approaches are also addressed in FCC 13-39 [22] and ARPANSA Radiation Protection Series Publication No. 3 [23]).

The approach described in this case study is applicable to a range of BS installations, including medium range BS as specified in [16] and [17] (see also Table C.1) and BS deployed in the street, called street cells. The assessed product is a 4G/LTE outdoor base station with a rated maximum transmitted power of 20 W, operating in the 750 MHz frequency band and intended to be used together with an omni-directional antenna with 5,1 dBi gain, see Figure 8. The assessments were performed using methodology specified in 6.1 and 8.2 (IEC 62232:2017). The results of the RF electromagnetic fields (EMF) exposure assessment were compared with the ICNIRP basic restriction and reference levels [8].



Figure 8 – Omni-directional antenna connected to the street cell product

10.2 Implementation of IEC 62232:2017

10.2.1 Evaluation process

This product compliance assessment follows the procedure as specified in 6.1 (IEC 62232:2017). Compliance boundary information is determined for the specified configuration of the BS product assuming free space conditions.

SAR measurements for localized exposure and spatially averaged field strength measurements for whole-body exposure were selected, and the procedures described in 6.1.5.2 and 6.1.5.3 (IEC 62232:2017) were used.

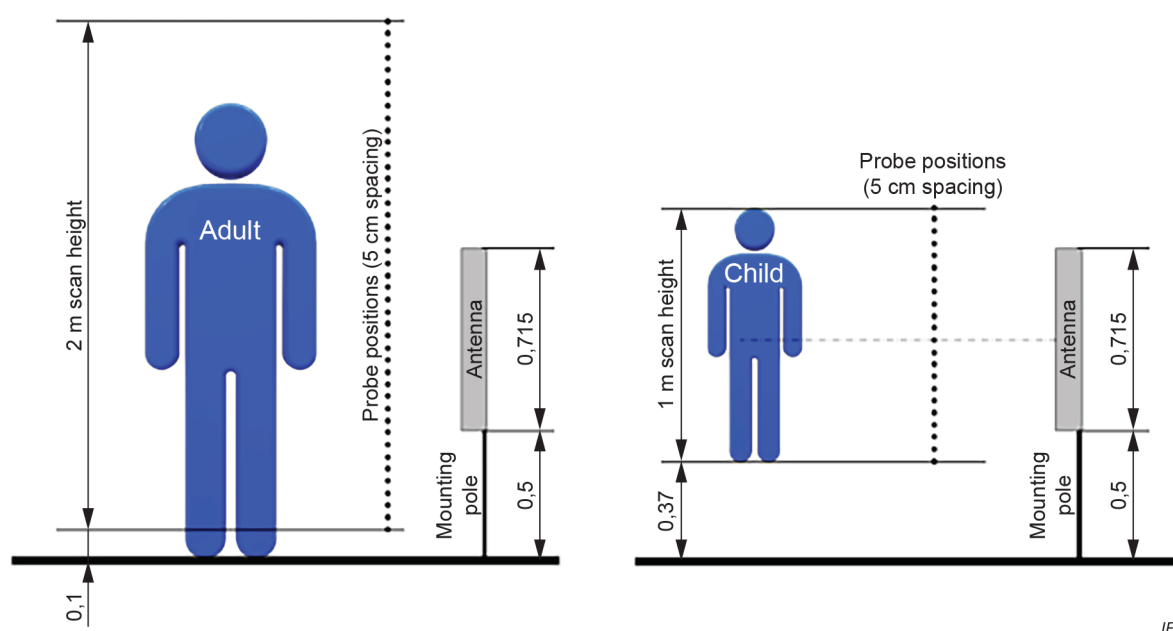
10.2.2 Methodology

During both the localized 10 g SAR measurements and the spatially averaged field strength measurements, the transmitter was replaced by a signal generator that was able to generate the rated maximum transmitted power (20 W) over the same frequency range.

The SAR measurements were performed in a flat phantom sufficiently large to cover the whole antenna according to B.3.2.2.2 (IEC 62232:2017). Different separation distances were assessed in order to determine the distances for compliance with head and body as well as limb SAR limits for the general public as specified in B.3.2.2.4 (IEC 62232:2017).

Evaluations of the spatially averaged electric (E) and magnetic (H) field strength were performed by scanning of measurement probes along 1 m and 2 m long vertical lines parallel to the antenna (see Figure 9) at multiple separation distances. The different scan lengths were selected to represent child and adult exposure, respectively. The child scan was centred in relation to the antenna to represent a maximum whole-body exposure. The scan commenced at 37 cm above the base of the mounting pole to achieve this. The minimum height of the adult scan was 10 cm above the base of the mounting pole to avoid coupling between the probe and ground plane.

Dimensions in metres



IEC

Figure 9 – Vertical scan lines for spatially averaged field strength measurements

10.2.3 Reporting

The case study test report is provided in Annex E. The measurement uncertainty was determined according to 6.1.6 and Clause 9 (IEC 62232:2017), and the results were reported according to 6.1.7 and Clause 10 (IEC 62232:2017).

10.3 Technical outcome

The obtained compliance distances are provided in Table 5.

Table 5 – General public compliance distances for the street cell BS with omni-directional antenna

Product type	Frequency band rated maximum transmitted power	Antenna type and gain	RF compliance distance localized 10 g SAR limit for head and body	RF compliance distance localized 10 g SAR limit for limbs	RF compliance distance for spatially averaged field strength limits (child)	RF compliance distance for spatially averaged field strength limits (adult)
Street cell	750 MHz 20 W	Omni 5,1 dBi	20 cm	10 cm	74 cm	40 cm

Analysis of the measurement results showed that the compliance distance for the general public differs depending on whether children or adults will be accessing the area close to the antenna.

10.4 Validation study

10.4.1 Validation process

The objective of the validation study was to verify that the use of basic restrictions (i.e. localized 10 g SAR and whole-body SAR) provides consistent results with peak and spatially averaged field strength (E and H).

A study including whole-body SAR measurements was performed with the omni-directional antenna to validate the general public EMF compliance distance. This was obtained by measurements of spatial averaged field strength for the street cell product.

The laboratory whole-body SAR measurements were performed in a large box-shaped phantom using a SAR robot system, in accordance with B.3.2 (IEC 62232:2017), see report in Annex E. Measurements were performed at different separation distances between the antenna and the phantom to find the compliance distance applicable for general public (adult and child) exposure.

10.4.2 Comparison of spatial average field strength and whole-body SAR results

The results of the whole-body SAR assessment are presented in Table 5. The validation study test report is provided in Annex E.

The results show that a compliance assessment using the basic restriction whole-body SAR limit provides the smallest compliance distance also ensuring the most relevant comparison with basic restrictions. The use of the reference level spatial average field strength assessment is slightly more conservative. This result is consistent with the derivation of basic restrictions and reference levels.

In addition, peak field strength measurements were taken and provide the largest compliance distance, see Table 6.

Table 6 – Street cell EMF compliance assessment comparison: general public (adult) compliance distances based on SAR and field strength

Street cell rated maximum transmitted power	Localized 10 g SAR measurement (Laboratory 1)	Peak field strength measurement (Laboratory 2)	Adult whole-body SAR measurement (Laboratory 1)	Adult whole-body field strength measurement (Laboratory 2)
20 W	20 cm	114 cm	30 cm	40 cm

10.5 Lessons learned

The case study has verified that RF exposure evaluations based on basic restrictions provide more accurate results for small cell products by not overestimating the compliance distance. This can be used to manage access in close proximity to small cell antennas.

Spatial averaging schemes and assessment methods taking into account time and spatial averaging should be considered in the next edition of IEC 62232.

11 Macro site in-situ measurements

11.1 General description

A location of interest near a mobile phone base station (BS) had been identified for conducting an RF exposure assessment using *E*-field level measurements as specified in 6.3 (IEC 62232:2017). The BS site is a full macro site with three operators present and is located on the rooftop of a building in medium density retail/residential area (see Figure 10). The antennas are mounted 15 m above relative ground level.



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Figure 10 – View from the measurement location to the BS

There were three operators present at the BS site using multiple technologies as described in Table 7.

Table 7 – Operators and technologies present on the BS site

Operator	Technologies
A	LTE1800, WCDMA850,
B	GSM900, LTE1800, WCDMA900, UMTS2100
C	UMTS2100

The purpose of this measurement was to provide information regarding the *E*-field levels due to the BS, at the location of interest.

11.2 Implementation of IEC 62232:2017

11.2.1 Evaluation process

Using the quick start guide in 5.2 (IEC 62232:2017), the following steps for the measurement campaign were identified.

- Test type: 6.3 (IEC 62232:2017) – In-situ RF exposure assessment.
- Test method: 8.2 (IEC 62232:2017) – Field strength measurements.
- Field strength measurement method: B.3.1.2 (IEC 62232:2017).
- Extrapolation: B.5 (IEC 62232:2017).
- Time averaging: 6.4.2 (IEC 62232:2017).
- Multiple frequency summation B.6 (IEC 62232:2017).
- Measurement uncertainty: Clause 9 (IEC 62232:2017).
- Reporting: Clause 10 (IEC 62232:2017).

11.2.2 Methodology

A location of interest was identified for the measurement. As it was a specific question regarding the *E*-field levels due to the BS, there was no need to consider other sources in the environment. The technologies present at the site were confirmed with the respective mobile operators.

The average level for each of the channel bands and control channels for the technologies present were measured using a frequency selective device. Measurements were performed at 1,1 m, 1,5 m and 1,7 m above relative ground level between 12:00 and 14:00 on a business day. These measured levels were then used to determine the indicative average cumulative RF exposure level and the maximum possible RF exposure level.

11.2.3 Reporting

A typical test report according to Clause 10 (IEC 62232:2017) template and detailing the measurement methodology and results is provided in Clause F.2.

11.3 Technical outcome

The measurements were able to provide information regarding the *E*-field levels due to the BS at the location of interest. The results of the measurements at 1,5 m above relative ground level are shown in Table 8.

Table 8 – Measurement results for 1,5 m above relative ground level

Result type	Measurement results	
	V/m	W/m ²
Measured time-averaged maximum	1,8	8,2
Measured extrapolated maximum	2,4	15,2
NOTE Measured time-averaged maximum values are real time measured values using 1 min time-averaging of the cumulative RF-EMF exposure level due to all mobile services present in the environment. Measured extrapolated maximum values are derived from the extrapolated measured control channels present for the site under test representing the possible maximum level based on the measurements according to B.5.5 (IEC 62232:2017).		

11.4 Lessons learned

The desired in-situ measurement was performed appropriately using IEC 62232:2017.

For the next edition of IEC 62232, it should also be considered to:

- provide more specific advice about the actual maximum values to be used, as specified in Clause 13;
- provide practical guidance for performing in-situ measurement campaigns on 5G macro BS using massive MIMO.

12 Macro site in-situ measurements using drones

12.1 General description

This case study provides an example of evaluation of RF exposure assessment of base stations with the help of a drone, which is an emerging technology that supplements the existing measurement methods described in B.3.1 (IEC 62232:2107).

The purpose of this case study is to illustrate how to measure the electromagnetic exposure of the base stations with the help of a drone. The measurement methods of electromagnetic environment currently used are mostly ground-based measurements. In recent years, drone-based measurements are widely used. A drone carrying an *E*-field test equipment can be used to perform measurements at altitude provided that it can hover and collect measured data at any position in the air. More importantly, the drone can overcome the challenges of an adverse geographical environment. It can also be quickly directed to locations that are otherwise difficult to access and determine electromagnetic exposure.

The measurement process and considerations are introduced as an example in this document.

NOTE Drone-based measurements are performed in accordance with national aviation regulations. These aspects are not addressed in this document.

12.2 Implementation

12.2.1 Evaluation system

The drone-based measurement system illustrated below consists of the drone, remote controller, probe, camera and a ground-based laptop (see Figure 11). This is representative of the main components of a system, where the drone is acting as a 3D positioning system while the probe and measurement system are similar to any kit used in a handheld in-situ measurement scenario.

Selection of the components used is critical as they all have interdependencies such as interference from the drone control systems and the RF probe measurement and also the 3D positioning can be verified by two independent systems to increase accuracy. The uncertainties of the various components and the overall system have not been addressed in this document. They should be considered in future revisions of IEC 62232 as the available systems become more established.

Multiple trials have been completed in Belgium, China and France, all using unique configurations of drones, RF probes, spectrum analysers and control systems. Each trial was designed to address and overcome various areas of practicality and measurement uncertainty, e.g. flying autonomously removed the need for wireless communications with the drone, thus avoiding interference with the measured fields.

In the example illustrated here, the laptop was equipped with a transponder to communicate with the drone, and the measurement software was also installed on the laptop. The technical components of the measurement system are provided in Clause G.1.

The frequency range of the airborne probe is 30 MHz to 6 GHz; however, the frequency of the remote-control signal of the drone is 2,4 GHz. To keep the probe free from interference, a directional antenna is mounted on the drone to communicate with the ground.

The multi-rotor drone was selected for these measurements in consideration of the needs for measurement activities. In particular:

- it can lift-off vertically to the target point;
- the lifting speed and flight attitude can also be controlled by changing the speed of each motor.

The technical parameters of the drone are provided in Clause G.2.