IEC TR 62669

Edition 2.0 2019-04

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

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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- withdrawn,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.

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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 >> 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 (°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 Ω (approximately 120π Ω)
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 *Groupe Spécial Mobile*)

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

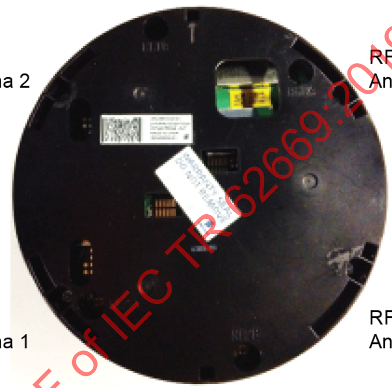
Clause	Annex (incl. test reports)	Base station type	Evaluation type with IEC 62232:2017 reference	Evaluation method with IEC 62232:2017 reference
6	Annex A	Small cell (indoor local area BS)	Product compliance (6.1)	SAR measurements (B.3.2)
7	Annex B	Small cell (outdoor medium range BS)	Product compliance (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.

a) Lateral view with radome included



b) Front view with radome removed

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.

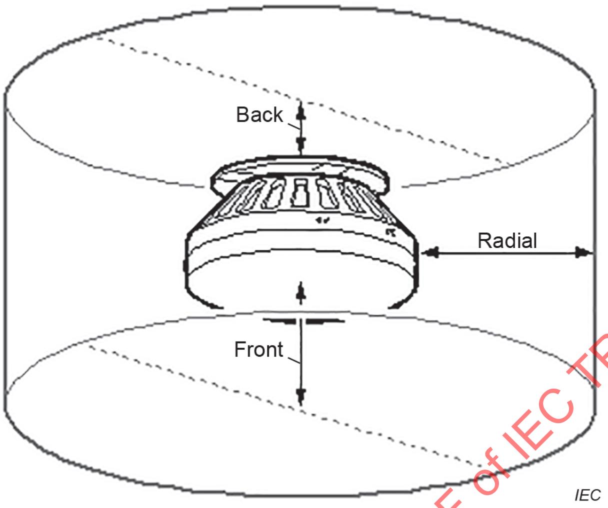


Figure 2 – Definition of cylindrical RF compliance boundary

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.

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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 3GGP 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

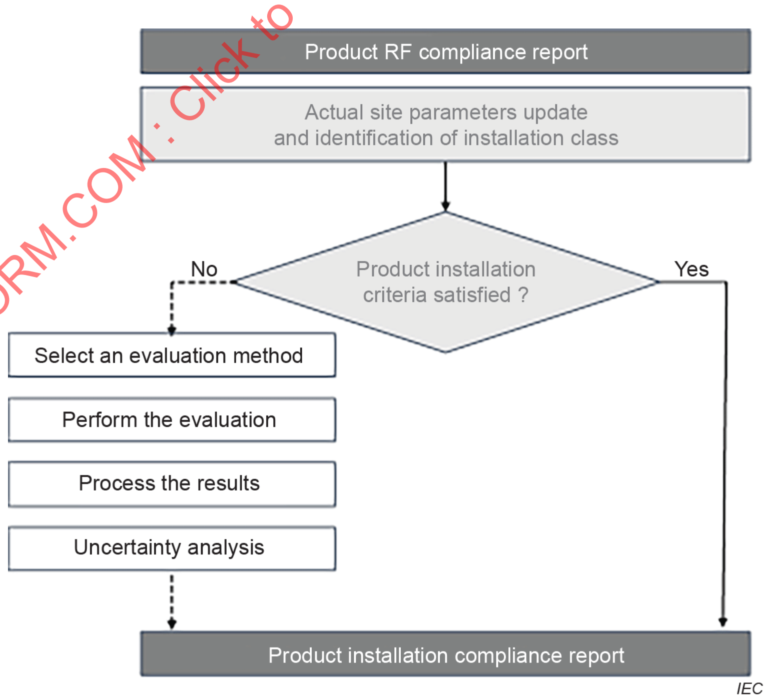
8.2 Implementation of IEC 62232:2017

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.

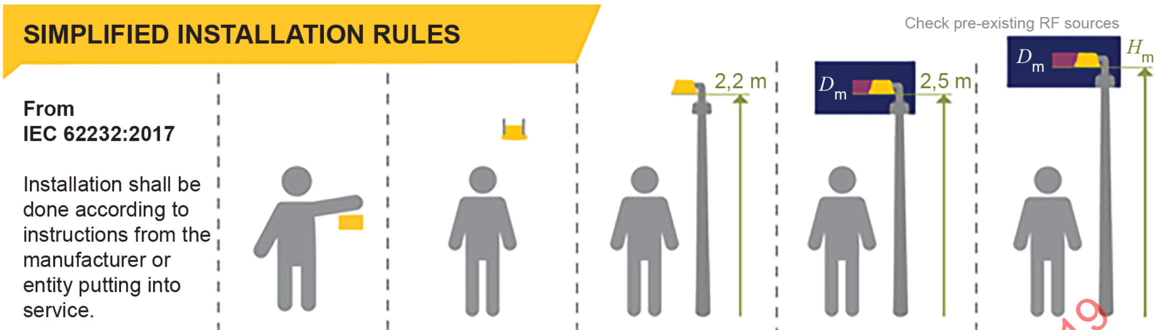
The process is derived from IEC 62232:2017 and represented in Figure 4. Once the BS product RF compliance boundary has been assessed based on 6.1 (IEC 62232:2017), the entity putting the BS into service can use the criteria specified in Table 2 (IEC 62232:2017) for assessing compliance without the requirement 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).



Installation class	E0	E2	E10	E100	E+
Total EIRP	None	≤ 2 W	≤ 10 W	≤ 100 W	No limit
Minimum height above walkway	None	None	2,2 m	2,5 m	H_m (calculation)
Exclusion zone	None, touch compliant	Provided in manufacturer's instructions small D_m not shown on the picture		Provided in manufacturer's instructions D_m in main lobe direction	
Check pre-existing RF sources	N/A	N/A	N/A	$5D_m$ in main lobe direction D_m in other directions	

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[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.

a) Indoor b) Outdoor 2 m to 4 m c) Outdoor > 4 m

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].

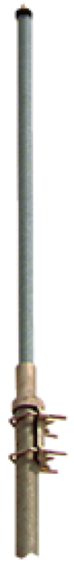

Figure 8 – Omni-directional antenna connected to the street cell product

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

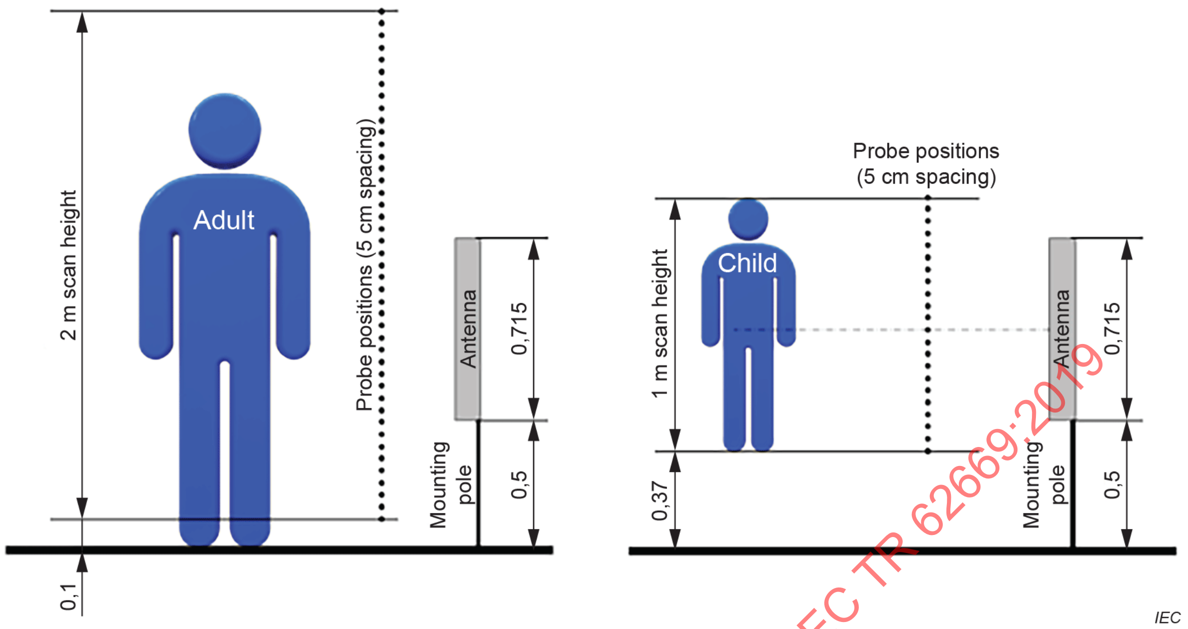

Figure 9 – Vertical scan lines for spatially averaged field strength measurements

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 transmit-ted 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.

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.

a) Test type: 6.3 (IEC 62232:2017) – In-situ RF exposure assessment.

b) Test method: 8.2 (IEC 62232:2017) – Field strength measurements.

c) Field strength measurement method: B.3.1.2 (IEC 62232:2017).

d) Extrapolation: B.5 (IEC 62232:2017).

e) Time averaging: 6.4.2 (IEC 62232:2017).

f) Multiple frequency summation B.6 (IEC 62232:2017).

g) Measurement uncertainty: Clause 9 (IEC 62232:2017).

h) 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:

a) provide more specific advice about the actual maximum values to be used, as specified in Clause 13;

b) 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.

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Figure 11 – Drone used for field measurements around the BS site

The base station site has been selected in an area where drones are permitted. The details of the site are provided in Clause G.3.

12.2.2 Evaluation process and methodology

In the measurement process, the drone flew around the base stations under test where the flying height was set at 25 m with a surrounding radius of 6 m. At each of the selected six measurement points, the drone hovered for 10 s and the premeasurement recording was performed every second. The measurement steps are shown in Clause G.4.

The measurement process can be automated using software installed in the laptop and can be switched to manual control mode by the tele-controller at any time. Airborne cameras are available for the real-time filming of the base station. The remote-controller and laptop used in the measurement system are shown in Clause G.4. The measurement software interface is shown in Clause G.5.

12.2.3 Reporting

Reporting was performed according to Clause 10 (IEC 62232:2017).

12.3 Technical outcome

The measurement results of the selected six measurement points are shown in Table 9.

Table 9 – The measurement results of the measurement points

Measurement points	1	2	3	4	5	6
Time-averaged power density (W/m^2)	0,027	0,144	0,176	0,033	0,016	0,031

From Table 9, the measured values of all the points are much less than 0,4 W/m^2. Therefore, this base station complies with national standard GB 8702-2014 [24] of People's Republic of China. The measurement results show that the drone-based measurement is a good complement to the existing measurement methods.

12.4 Lessons learned

The results show that the measurements can be accomplished effectively by the drone-based electromagnetic environment measurement system. Considerations for improvement of the measurement system and process are provided in Clause G.6.

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

a) a method to realize spatial and time averaging using drones;

b) how many measurement points are needed to define accurately the compliance distance;

c) a recommendation about how to proceed when antennas on a mast are at different heights.

d) recommendations for performing the uncertainty analysis.

13 RF exposure assessment based on actual maximum transmitted power or EIRP

13.1 General guidelines

13.1.1 Technical background and rationale

The level of RF power transmitted by a BS in a mobile network varies with time in order to optimize the service to user equipment (UE) whilst minimizing the interference to neighbouring cells. The ability to reduce the average transmitted power also enables reduced energy consumption of mobile networks and related operational expenses, a key requirement for mobile network operators. When designing a mobile network and defining the set-up parameters of a BS, operators generally consider the power budget margins. For instance, each BS typically operates below its medium capacity level (e.g. 50 %) to have enough margin to address occasional traffic peaks without reaching traffic congestion that can occur at full capacity.

In general, the RF signals transmitted by a BS include control channels or reference signals that are necessary to identify the presence of UE and grant them access to the network. This signaling specifies the minimum level of power that the system shall transmit for the appropriate functioning of the mobile technology. On the other hand, each BS has a maximum level of RF transmitted power that it can deliver to connected UE within its coverage area.

Mobile network management systems including the network manager provide counters representing the performance and operation of the system. Statistics can be generated for one single cell or multiple cell sites distributed over a very large geographical area. Among the many available counters, the downlink transmitted power (i.e. total power transmitted from the BS towards the UEs) is the most valuable for RF exposure investigations. The transmitted power varies on a cyclical manner: on a daily basis (e.g. with minimum and maximum traffic in the early morning around 3 am or 4 am, and during rush hours, respectively), on a weekly basis (e.g. for locations where people stay during the weekend or on high traffic highways) or on a more seasonal basis (e.g. BS deployed in seasonal touristic areas). Typical traffic profiles have been published in the technical literature [25] and considered in international standards, e.g. ETSI ES 202 706-1 [26].

The impact of traffic variation on RF exposure conditions for mobile technologies has also been reported in various publications [27], [28], [29], [30], [31] and [32], and is addressed in 6.4.2, 6.3.2.3.3, B.3.1 and Clause B.5 (IEC 62232:2017).

Example CDFs of the time-averaged transmitted power obtained from network-based measurements from a 3G network in India [31] are shown in Figure 12. Similar results from network-based measurements of a 2G/3G/4G network in Sweden are shown in Figure 13. These CDFs have been obtained by combining the data from a large number of cells in the network.

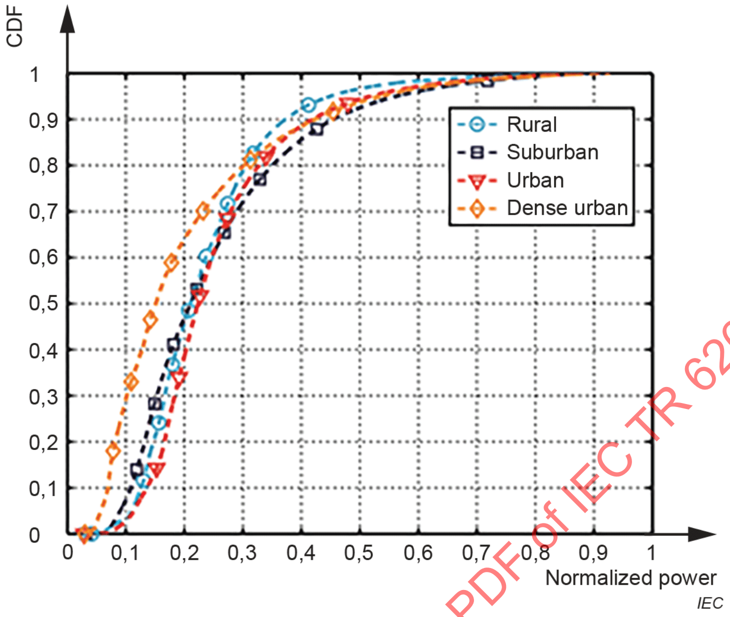


Figure 12 – Empirical CDFs of transmitted power (normalized) for different environments in 3G network in India [31]

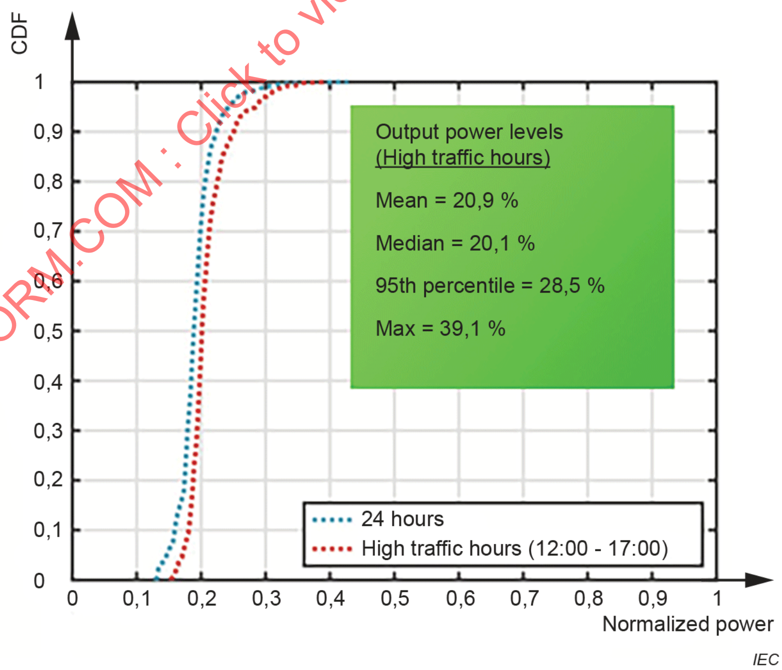


Figure 13 – Empirical CDFs of combined transmitted power (normalized) for a 2G/3G/4G network in Sweden [32]

Statistical analysis of RF exposure from multiple technologies has also been presented in [27]. The objective was to develop the CDF of extrapolation factors for various technologies, as well as for the combined exposure assessment. Figure 14 shows that the extrapolation factor for HSDPA technology combined with other preexisting technologies is lower than the extrapolation factor for HSDPA alone.

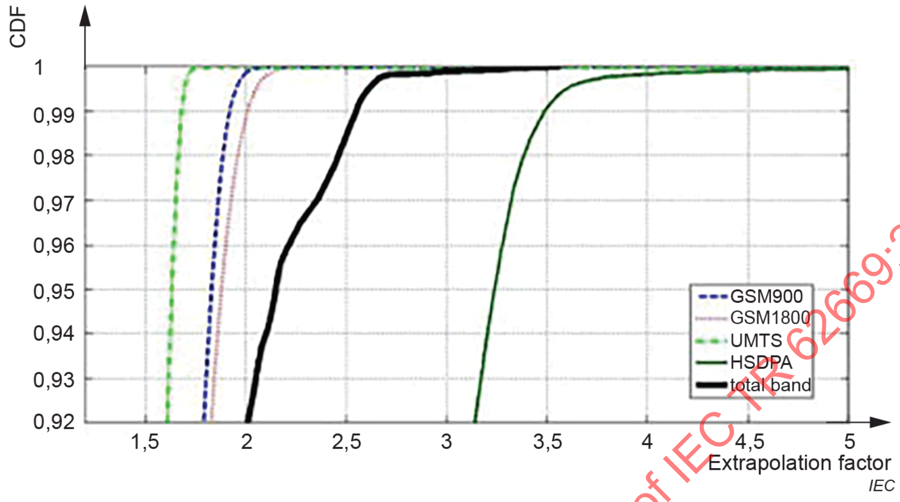


Figure 14 – Extrapolation factor of the power flux density $S(t)$ of the different signals and the $S_{total}(t)$ (all bands) with a sliding time averaging of 6 min applied to the measurements [27]

Base stations with mMIMO antennas produce a number of simultaneous narrow beams individually steered towards target devices in order to optimize the usage of radio resources by focusing radio energy to target users and reducing interference to other devices. This "beam-centric" behaviour of mMIMO systems differs from conventional radio access technologies for which energy is constantly transmitted in a wide angular sector. This dynamic focusing of energy in different individual directions will also impact the actual exposure of mMIMO base stations. BS with mMIMO use many antenna elements to spatially multiplex users by transmitting RF energy in narrow beams. Different type of beamforming can be implemented such as the grid of beam approach (code book based), which allows to create narrow high gain beams toward the users, and eigen-beamforming (EBB) and zero forcing (reciprocity based), which takes into account the multi-path properties of the wireless channel. With BS using mMIMO, the transmitted power is spread in different directions to provide service to different UEs in different geographic locations. Therefore, beamforming involves additional variability in the determination of the power contributing to the actual maximum exposure. The power reduction of a BS using mMIMO can be described by two factors: (i) the traffic variation and (ii) the time-averaged spatial distribution of transmitted power or EIRP.

Techniques to assess the actual maximum transmitted power or EIRP and actual maximum RF compliance boundary of a BS with mMIMO have been introduced in Clause F.10 (IEC 62232:2017). However, it was observed in the above mentioned publications [27], [28], [29], [30], [31] and [32], that the proposed approach for establishing compliance based on the actual maximum transmitted power introduced in Clause B.5 (IEC 62232:2017) is also applicable to BS with fixed beams. Guiding principles for conducting RF exposure assessment based on the actual maximum approach are provided in 13.1.2. More details on the methods and practical implementation examples are provided in 13.2 for modelling studies and 13.3 for measurement studies.

13.1.2 Guiding principles for conducting RF exposure assessment based on the actual maximum approach

From the measurement campaign results described in 13.1.1 and the case studies presented in 13.2 to 13.4, the real time-averaged transmitted power by BSs during service, called actual transmitted power, is generally below the time-averaged maximum transmitted power. Therefore, as a conservative approach, the actual maximum transmitted power can be used to determine the RF compliance boundary provided that the operator is implementing tools ensuring this threshold is not exceeded over time during service. These tools can be based on BS counters and features developed by manufacturers to monitor and control the RF transmitted power or EIRP and other relevant characteristics of the BS (see examples in 13.3.3.3). This applies to all types of BS, whether they are using fixed beams or steerable beams like with mMIMO. From the examples and case studies introduced in Clause 13, scenarios where the time-averaged transmitted power or EIRP is capped to the actual maximum threshold are expected to only occur occasionally in the mobile network, reducing the impact on services.

In this context, the next edition of IEC 62232 should consider defining methods for performing an RF exposure assessment of any type of BS using the actual maximum transmitted power or EIRP. The following implementation process should be considered.

a) The operator specifies the actual maximum transmitted power or EIRP threshold(s) for a BS site sector or sub-divisions of a BS site sector for mMIMO using the following options:

   1) use the maximum value of the measured time-averaged transmitted power or EIRP, if the CDF is known from measurements on the BS itself or on one single BS with similar configurations and environments (see 13.3);

   2) use a percentile (e.g. 95th or other value to be determined by the operator or by the national regulatory agency) of the CDF, if the CDF is derived from measurements on a representative large sample of BS sites;

   3) otherwise, use a percentile (e.g. 95th or other value to be determined by the operator) of the CDF, if the CDF is derived from computation models on BS sites with similar configurations and environments (see 13.2).

b) Before putting the BS into service:

   1) the operator evaluates the RF compliance boundary using the actual maximum transmitted power or EIRP threshold(s) specified in a) and records the assessment parameters and results, including the CDF, as specified in 6.2 (IEC 62232:2017);

   2) the operator configures the BS and implements tools ensuring that the time-averaged transmitted power or EIRP does not exceed the time-averaged actual maximum transmitted power or EIRP threshold(s) over time specified in step a) and declared in b) 1).

c) During the BS service:

   1) the network operator records periodically the CDF of the time-averaged transmitted power or EIRP;

   2) the BS actual maximum transmitted power or EIRP threshold(s) and the records of the CDF of the time-averaged transmitted power or EIRP are made available in the assessment reports;

   3) if the operator intends to increase the configured actual maximum transmitted power or EIRP threshold(s), the RF compliance boundary is updated using step b), and where required by national regulation, the appropriate authorities are informed.

13.1.3 EIRP evaluation assumptions

During antenna system operations, the antenna gain, beam direction and transmitted power are varying in time, azimuth and elevation. The time-averaged EIRP depends on deterministic factors (P_{TXM}, F_{TDC} and G_{MLB}) and factors (F_{PDL} and F_{G}) which can be deterministic for BS using fixed beams or variable in azimuth and elevation for BS using steerable beams such as mMIMO.

The time-averaged EIRP is calculated using Equation (1):

$$\text{EIRP}\ (\theta,\ \phi) = P_{\text{TXM}} \times F_{\text{TDC}} \times G_{\text{MLB}} \times F_{\text{PDL}}\ (\theta,\ \phi) \times F_{\text{G}}\ (\theta,\ \phi) \qquad (1)$$

where

θ	is the azimuth;
ϕ	is the elevation;
P_{TXM}	is the maximum transmitted power in downlink (deterministic factor);
F_{TDC}	is a scaling factor representing the technology duty cycle of the signal (deterministic factor);
G_{MLB}	is the maximum gain in the main lobe for fixed beam or boresight for steerable beams (deterministic factor);
$F_{\text{PDL}}\ (\theta,\ \phi)$	is the normalized downlink transmitted power $F_{\text{PDL}}\ (\theta,\ \phi,\ t)$ averaged on the time interval T;
$F_{\text{G}}\ (\theta,\ \phi)$	is the normalized variable part of the gain $F_{\text{G}}\ (\theta,\ \phi,\ t)$ averaged on the time interval T;
t	is time;
T	is the time interval used for time averaging.

The variable factors are represented by the normalized EIRP factor as defined in Equation (2):

$$F_{\text{EIRP}}\ (\theta,\ \phi) = F_{\text{PDL}}\ (\theta,\ \phi) \times F_{\text{G}}\ (\theta,\ \phi) \qquad (2)$$

The power reduction factor is derived from the statistical analysis (CDF) of the time-averaged transmitted power and therefore does not include deterministic factors such as the technology duty cycle factor. The actual maximum transmitted power is derived from the maximum transmitted power (generally corresponding to the rated maximum transmitted power if there is no feeder loss) using Equation (3):

$$P_{\text{TXAM}} = P_{\text{TXM}} \times F_{\text{TDC}} \times F_{\text{PR}} \qquad (3)$$

where

P_{TXAM}	is the actual maximum transmitted power;
F_{PR}	is the power reduction factor.

13.1.4 Technology duty cycle factor assumptions

The technology duty cycle factor F_{TDC} represents the maximum time used for transmission of signals for a given period at full load. It depends on both the technology being used (GSM, UMTS, LTE-TDD, LTE-FDD or NR) and on the operator's implementation of the technology.

Figure 15 represents a generic structure of a frame, showing multiple transmission periods (marked Tx ON) in a frame and periods when there is no transmission because the BS is either in receiving mode (in TDD) or it corresponds to guard time between operation modes. P_{TXM} is the maximum transmitted power of the BS when the transmitter is ON, i.e. during time interval $T_{\text{TX}i}$. More accurate figures can be derived from specifications 3GPP TS 36.211 for LTE [4] and 3GPP TS 38.211 [5] for NR. Figures F.8 and F.10 (IEC 62232:2017) also provide indications for LTE-TDD and LTE-FDD, respectively.

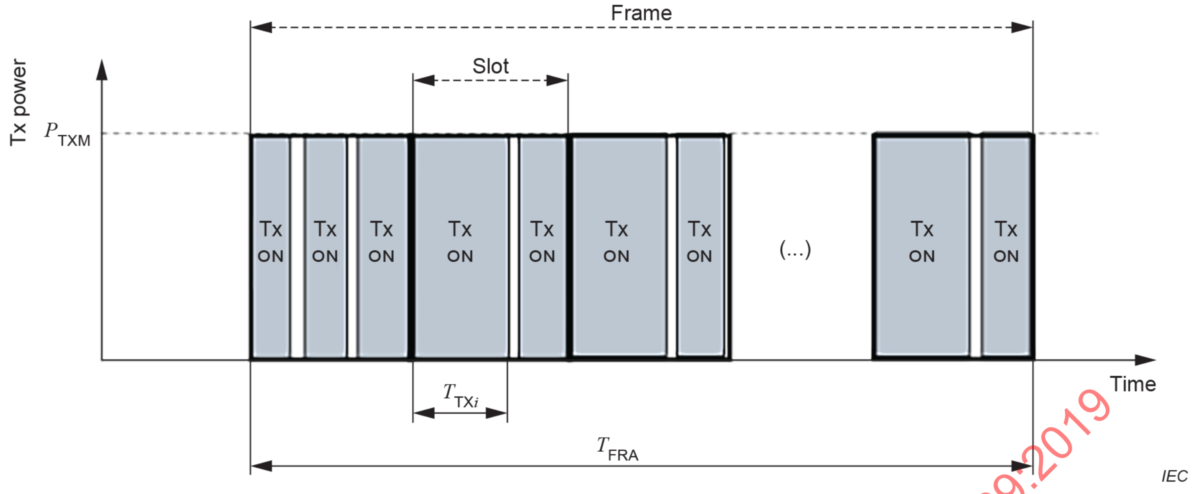


Figure 15 – Generic structure of a base station transmitted RF signal frame

The general formula for F_{TDC} is given in Equation (4):

$$F_{TDC} = (\Sigma_{i,\ Frame}\ T_{TXi}) \ /\ T_{FRA} \tag{4}$$

where

F_{TDC} is the technology duty cycle factor;

T_{TXi} is the ith element of transmitted signal in the frame;

T_{FRA} is the duration of a frame.

For GSM and UMTS mobile technologies, the default value for F_{TDC} is 1.

For LTE and NR mobile technologies, the transmission (Tx) periods are used to convey the signal to users (PDSCH) but also downlink control channel (PDCCH), broadcast channel (PBCH) and reference signals used for synchronization purposes. More details can be found in 3GPP TS 36.211 [4] for LTE and 3GPP TS 38.211 [5] for NR.

For LTE-FDD and NR-FDD, the approximated value of F_{TDC} is 1.

For LTE-TDD and NR-TDD, the approximated value of F_{TDC} is provided by Equation (5).

$$F_{TDC} \approx T_{DL}/(T_{DL} + T_{UL}) \tag{5}$$

where

T_{DL} is the total duration of the downlink signal per frame;

T_{UL} is the total duration of the time period used for uplink per frame.

For example, for TDD Configuration 2 described in Table F.11 (IEC 62232:2017), there is one uplink (UL) time period for three downlink (DL) periods, resulting in a duty cycle factor of 75 %. Typical values of F_{TDC} are between 0,75 and 0,8 depending on the special subframe format implemented. When the exact value is not specified, an approximated value of 0,75 (i.e. 3/(3+1)) can be chosen using Equation (5) approximation.

13.1.5 Expected outcome of actual maximum approaches

The outcomes of actual maximum approaches (from computation models or measurements) are expected to include the following information:

a) the CDF of the normalized EIRP distribution or the CDF of the normalized transmitted power distribution (if it can be assumed that F_G = 1 as a practical overestimate);

b) percentile(s) of the normalized EIRP distribution, including at least the actual maximum transmitted power or EIRP according to the principles specified in 13.1.2. In situations where the full CDF is used, for example when conducting statistical combinations of multiple transmitters (see 13.4), at least the 5th, 25th, 50th, 75th, 95th and 99th percentiles are recommended;

c) RF compliance boundary assessed according to IEC 62232:2017 using the actual RF maximum transmitted power or EIRP, taking into account the deterministic factors (see Equation (1)) and all foreseeable beam steering directions. The RF compliance boundary can be described with various shapes as specified in 6.1.2 (IEC 62232:2017).

13.2 Modelling studies for BS using mMIMO

13.2.1 Guiding principles

Based on the compliance approach introduced in 13.1.2, the actual maximum transmitted power for BS can be established using modelling studies. When performing such modelling studies on BS using mMIMO, the number, position, duration of service, and movement of each user are all relevant statistical factors. These factors influence the average power per beam during a time-period corresponding to the averaging time T in the relevant EMF guidelines. The spatial distribution of UEs and traffic generation follows scenarios that can be derived from 3GPP standards such as [6], [7] or dedicated papers [33], [35].

The main evaluation steps for performing modelling studies are:

a) define the set of parameters relevant to conduct traffic modelling and RF exposure assessment of a mMIMO site or site cluster for a given mobile system technology;

b) evaluate the statistical distribution of the transmitted power or EIRP, and derive the actual maximum transmitted power or EIRP;

c) derive the actual maximum RF exposure and the corresponding RF compliance boundary.

13.2.2 Simulation model parameters

Usual parameters for conducting an RF exposure calculation according to IEC 62232:2017 need to be complemented by new parameters defining the realistic operation of the base station site or site cluster. Table 10 provides an example of the simulation parameters generally used for statistical analysis.

Table 10 – Relevant parameters for conducting RF exposure modelling studies of a massive MIMO site or site cluster

Type	Simulation model parameters	Example(s)	Proposed for inclusion in next edition of IEC 62232
General	Technology	5G NR TDD or LTE-TDD	
	Technology duty cycle	0,75	x
	Use case	Mobile broadband	x
	Environment type	Urban or sub-urban or rural	x
	Frequency	3,6 GHz (3GPP Band 42) or 2,6 GHz (3GPP Band 38)	
Site	Installation height	10 m	
	Number of sectors per site	1 or 3	
Site cluster	Number of sites	1 or 7	
	Cell shape	Hexagonal	x
Antenna	Type	2D array antenna with 32 cross polarized radiating elements: 4 columns × 8 rows	
	Dimension of the array antenna panel	30 cm × 60 cm	
	Maximum gain in the main lobe	24 dBi	
	Horizontal half-power beamwidth (HPBW-H)	12,3°	
	Vertical half-power beamwidth (HPBW-V)	8,1°	
	Beam steering range (azimuth)	90°	x
	Beam steering range (elevation)	40°	x
Radiating element	Gain	8 dBi	x
	Horizontal half-power beamwidth (HPBW-H)	70°	x
	Vertical half-power beamwidth (HPBW-V)	70°	x
Equipment transmitter	Rated maximum transmitted power	100 W (50 dBm)	
	Rated maximum transmitted EIRP	74 dBm	
System simulations	Beamforming type	Grid of beam	x
	Channel model / traffic load	Full buffer / 100 %	x
	Number of simultaneously served UEs	1 or 5 or more	x
	UE spatial distribution law	Normal	
	UE indoor/outdoor ratio	80 % indoor, 20 % outdoor	x
	UE service duration	30 s	x
	Model operation duration[a]		x
	Time averaging period[b]	6 min	
	Contributions from adjacent and other beams (from IEC 62232:2017, Annex F.10)	Included	

[a] Model operation duration is not the simulation processing time; rather, it is the time interval used to model the realistic operation of the BS.

[b] The time averaging period recommended by RF exposure limits is frequency dependent and decreases in the millimetre wave frequency range. For example, in ICNIRP guidelines [8], the recommended time averaging period is 6 min up to 10 GHz and then decreases using the following formula: $68/f^{1,05}$ min period (where f is the frequency in GHz).

Examples of modelling case studies of BS using mMIMO antennas are provided in 13.2.3 to 13.2.5.

13.2.3 Modelling case study A

Simulation method A including its rationale and representativeness to 5G use cases are described in [33]. A mobile communication system employing mMIMO is modelled. A theoretical derivation of the statistically conservative fraction of total transmitted power contributing to the EMF exposure within an arbitrary beam is presented. The model considers the effects of BS utilization, technology duty cycle (TDD), and scheduling time. The spatial distribution of served users in azimuth and elevation corresponding to rural and urban installation scenarios is also a consideration. The relevant simulation parameters are described in Table 11.

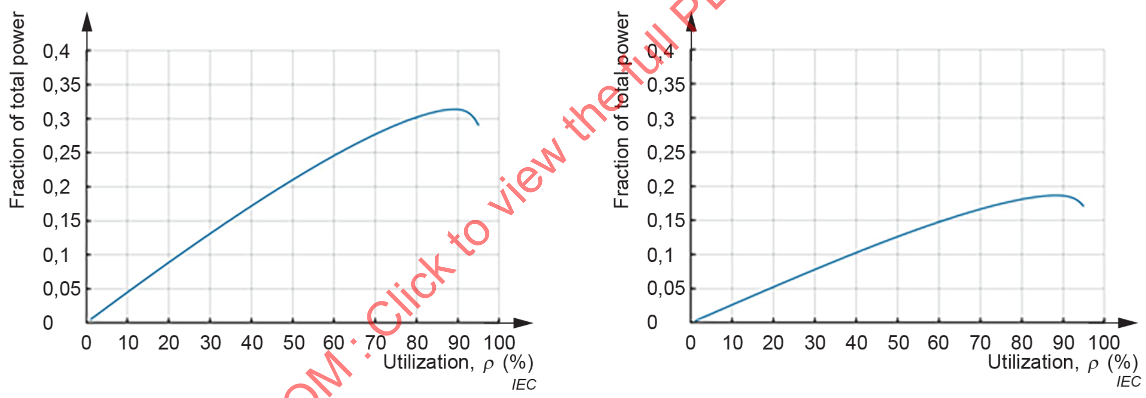
Table 11 – Relevant parameters for conducting RF exposure assessment of massive MIMO site according to simulation method A (from [33])

Type	Simulation model parameters	Specification
General	Technology	5G technology with mMIMO
	Technology duty cycle	Parameter, 75 % selected as typical value
	Use case	Mobile broadband
	Environment type	Urban and rural
	Frequency	3 GHz to 6 GHz
Site	Installation height	Model not dependent on installation height
	Number of sectors per site	Not used in the case study
Site cluster	Number of sites	1
	Cell shape	Not applicable
Antenna	Type	Square-shaped array antenna with 8×8 elements. Impact of array size analysed.
	Dimension of the array antenna panel	$4\lambda \times 4\lambda$ where λ is the wavelength
	Maximum gain in the main lobe	23 dBi
	Horizontal half-power beamwidth (HPBW-H)	12,7° (central beam)
	Vertical half-power beamwidth (HPBW-V)	12,7° (central beam)
	Beam steering range (azimuth)	120°
	Beam steering range (elevation)	30°
Radiating element	Gain	8 dBi
	Horizontal half-power beamwidth (HPBW-H)	73°
	Vertical half-power beamwidth (HPBW-V)	73°
Equipment transmitter	Rated maximum transmitted power	Parameter, model applicable for far-field exposure
	Rated maximum transmitted EIRP	Parameter, model applicable for far-field exposure
System simulations	Beamforming type	Grid of beams
	Channel model / traffic load	Parameter
	Number of simultaneously served UEs	Statistical model
	UE spatial distribution law	Models corresponding to urban and rural installation scenarios
	UE indoor/outdoor ratio	Not applicable
	UE service duration	Statistical model
	Model operation duration	Steady state solution
	Time averaging period	6 min
	Contributions from adjacent and other beams (from IEC 62232:2017, Annex F.10)	Included

The results for rural and urban scenarios are provided in Figure 16 and Figure 17, with the first case corresponding to a rural mMIMO installation, and the second to an urban installation. The graph to the left shows the expected (statistically conservative, probability larger than 95 %) fraction of the power transmitted in the broadside beam direction (including contributions from adjacent beams and side lobes) for a scenario when users are distributed horizontally with the highest density towards the broadside and without vertical beam scanning. The graph to the right shows the results for a scenario where users are distributed both horizontally and vertically and with the highest density towards the broadside. The results are given as a function of the utilization of the base station, and the highest power fractions are obtained for utilization levels around 90 %. In real operation, the utilization (averaged over the EMF time period) of a BS is typically much lower; therefore, applying the peak values will add considerable conservativeness. The statistical model is based on a series where summation is carried out over the number of served users. As the utilization increases, more terms (users) need to be included for the series to converge and the relative importance of higher order terms increases. This in combination with the increasing steepness of the cumulative binominal distribution function for larger populations accounts for the fraction of total power reaching a plateau and then reducing slightly for higher utilizations

NOTE This effect is not observed for the limiting case of exposure assessed for frequencies above 6 GHz in the immediate vicinity of a small array antenna when all the available power goes through the appropriate averaging area. For this case an analytical solution is available, and the fraction of total power simply equals the utilization [34].

In Figure 17, the CDFs which correspond to the BS utilization resulting in the highest power reduction factor are provided.



a) Typical rural mMIMO installation with horizontal beam scanning and highest density of users in the broadside direction

b) Typical urban mMIMO site with both horizontal and vertical beam scanning

Figure 16 – Fraction of the total power transmitted in the broadside beam direction for rural and urban scenarios

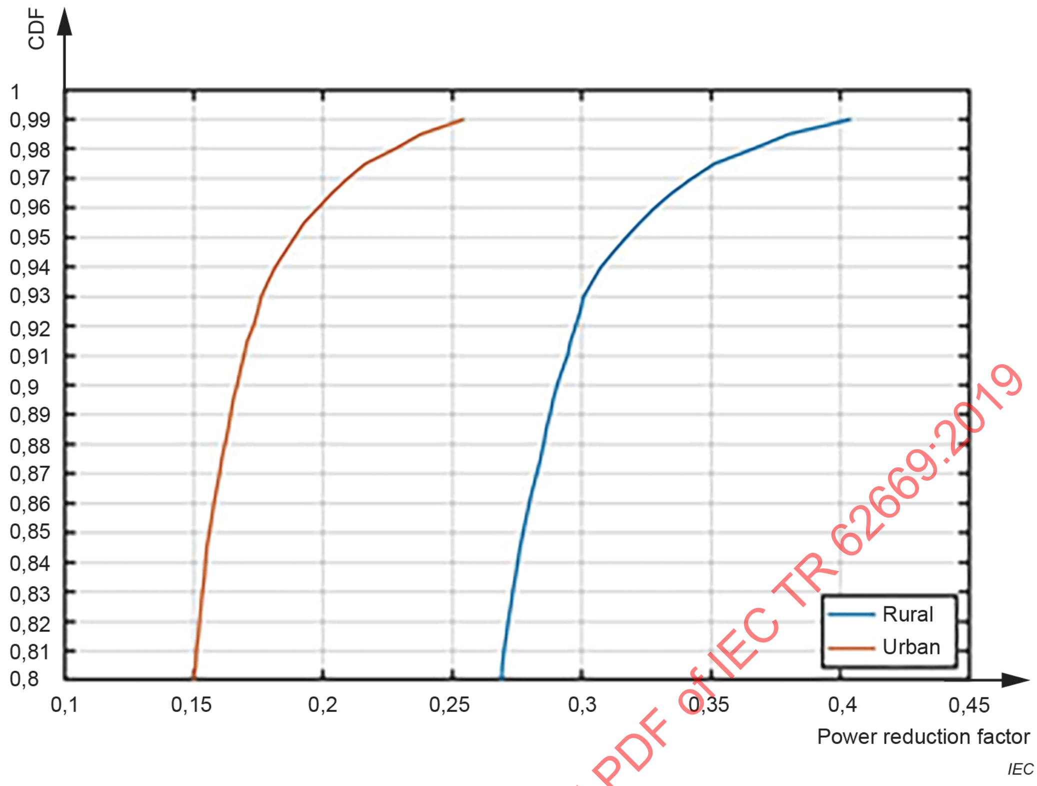


Figure 17 – CDF of the power reduction factor for rural and urban installation scenarios

The results were computed for an 8×8 mMIMO antenna designed to cover ±60° in azimuth and ±15° in elevation. The beam power fractions will be lower for antennas with more elements; however, the provided values can conservatively be applied for larger arrays when no specific statistical analysis is available.

Based on these results, a power reduction factor F_{DLP} of 0,32 can be used for rural mMIMO sites, and a factor of 0,19 for urban mMIMO sites. The effects of TDD can be considered by multiplying with a suitable technology duty cycle, e.g. F_{TDC} = 0,75, according to Equation (1).

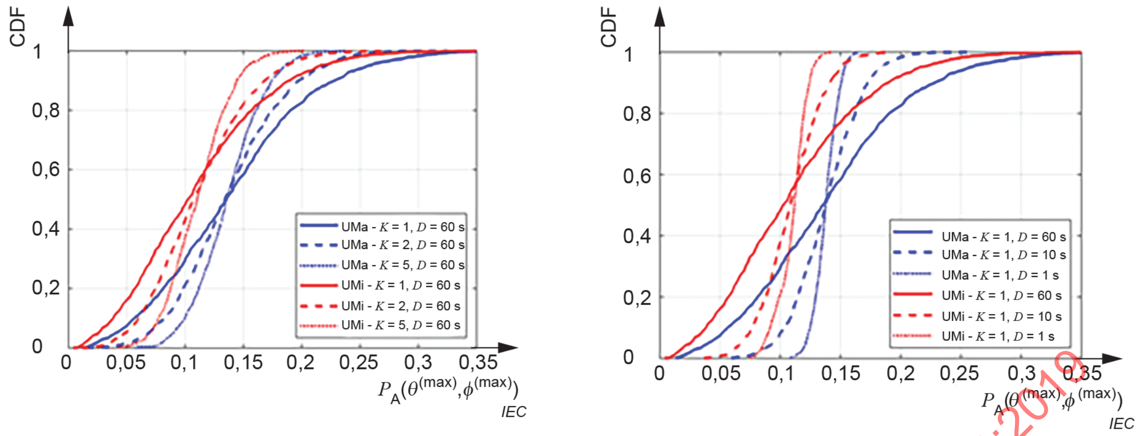
13.2.4 Modelling case study B

Simulation method B including its rationale and representativeness to 5G use cases are described in [35] and in 3GPP documents [6] and [7]. The deployment configurations and channel model simulation parameters are derived from 3GPP TR 36.873 [6] using Urban Macro (UMa) and Urban Micro (UMi) scenarios. These are consistent with 3GPP TR 38.901 [7], which is more recent. Table 12 provides the relevant simulation parameters.

Table 12 – Relevant parameters for conducting RF exposure assessment of a massive MIMO site or site cluster according to simulation method B (from [35])

Type	Simulation model parameters	Example(s)
General	Technology	5G OFDM
	Technology duty cycle	0,75
	Use case	eMBB
	Environment type	Urban Macro (UMa) and Urban Micro (UMi) as specified in 3GPP TR 36.873 [6] and 3GPP TR 38.901 [7]
	Frequency	2 GHz
Site	Installation height	25 m for UMa and 10 m for UMi (from [6] [7])
	Number of sectors per site	3
Site cluster	Number of sites	7
	Cell shape	Hexagonal
Antenna	Type	2D array antenna with 64 single polarized radiating elements: 8 columns × 8 rows
	Dimension of the array antenna panel	53 cm × 53 cm
	Maximum gain in the main lobe	26 dBi
	Horizontal half-power beamwidth (HPBW-H)	Not relevant for eigen-beamforming
	Vertical half-power beamwidth (HPBW-V)	Not relevant for eigen-beamforming
	Beam steering range (azimuth)	Within a 120° sector (3 sectors per site)
	Beam steering range (elevation)	Not relevant for eigen-beamforming
Radiating element	Gain	8 dBi
	Horizontal half-power beamwidth (HPBW-H)	65°
	Vertical half-power beamwidth (HPBW-V)	65°
Equipment transmitter	Rated maximum transmitted power	49 dBm and 44 dBm in UMa and UMi, respectively, on a system bandwidth of 20 MHz (from [6])
	Rated maximum EIRP	75 dBm and 70 dBm in UMa and UMi, respectively
System simulations	Beamforming type	Eigen-beamforming (EBB)
	Channel model / traffic load	Full buffer / 100 %
	Number of simultaneously served UEs (K)	1, 2 or 5
	UE spatial distribution law	Normal
	UE indoor/outdoor ratio	20 % outdoor 80 % indoor in nearby buildings whose height is uniformly distributed between 4 and 8 floors (from [6])
	UE service duration (D)	UE served for 1 s to 60 s
	Model operation duration	6 min
	Time averaging period	6 min
	Contributions from adjacent and other beams (from IEC 62232:2017, Annex F.10)	Included

The outcome of the modelling studies is summarized in Figure 18 and Table 13.



a) When the UE service duration D = 60 s and the number of simultaneously served UEs K = 1; 2; 5

b) When K = 1 and D = 1 s; 10 s; 60 s

Figure 18 – CDF of the normalized transmitted power for both UMa and UMi

Table 13 – Summary of the percentiles of the normalized transmitted power and compliance distances for a UMa scenario from 3GPP TR 36.873 [6] and 3GPP TR 38.901 [7]

UMa scenarios	**D = 60 s**		**D = 10 s**	
	K = 1	K = 5	K = 1	K = 5
50th percentile of normalized Tx power	0,13	0,13	0,13	0,13
95th percentile of Tx power	0,26	0,18	0,18	0,15
99th percentile of Tx power	0,32	0,19	0,19	0,16
Compliance distance based on the 95th percentile (m)	8,1	6,9	6,9	6,4
Reduction factor on the 95th percentile compliance distance	0,5	0,43	0,43	0,40
Compliance distance based on the 99th percentile (m)	9,0	7,3	7,3	6,6
Reduction factor on the 99th percentile compliance distance	0,56	0,45	0,45	0,41

Results in Table 13 demonstrate that for percentiles above 50 %, the CDF of the normalized transmitted power is higher in UMa compared to UMi. It also confirms that, for an 8×8 radiating element array, the 95th percentile of the transmitted power is 0,26 of the maximum transmitted power. The resulting reduction factor of the compliance distance is 0,5. When considering higher percentiles, for example the 99th percentile, the compliance distance remains within 11 % compared to the scenario based on the 95th percentile.

This modelling method also applies to BS using mMIMO with predefined grid of beams (GOB).

13.2.5 Modelling case study C

Simulation method C is described in [36]. Based on the Synthetic Model, mMIMO antennas can be understood as a simple array of point sources. These are distinguished into coherent and incoherent areas. The number of incoherent areas determines how many beams the antenna emits. Beam steering occurs by controlling the phases between elements of coherent areas [36]. In addition, the input power of the coherent areas is controlled differently.

All coherent areas have a phase parameter in horizontal and vertical directions. These parameters specify the phase shift to the neighbouring elements. Furthermore, each coherent area has an amplitude parameter.

All possible operating modes are considered functions of the two-phase shift parameters and the amplitude parameter per coherent area. For the distribution of the parameters, various functions can be used. As a conservative approach, a triangular distribution function has been chosen.

The procedure is based on the distribution functions of phase and amplitude values. Furthermore, an additional power reduction factor is varied between 0,1 and 0,9 and it is verified which proportion of configurations fulfils these values.

Detailed investigations have shown that for an antenna with 8×8 radiating elements, an additional power reduction factor of 0,4 is to be applied for the 95th percentile.

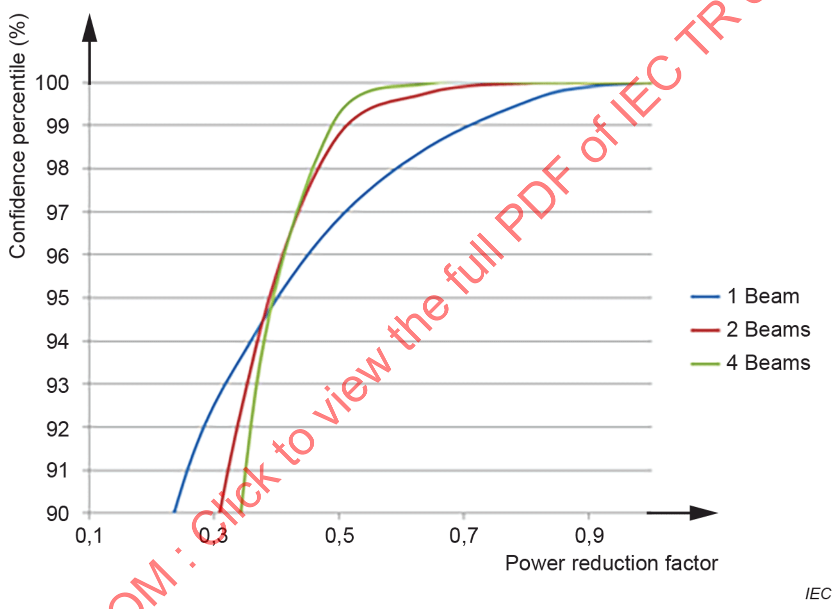
The relevant simulation parameters are described in Table 14.

Table 14 – Relevant parameters for conducting RF exposure assessment of massive MIMO site according to simulation method C (from [36])

Type	Simulation model parameters	Specification
General	Technology	mMIMO antenna
	Technology duty cycle	Not applicable
	Use case	Mobile broadband
	Environment type	Urban and rural
	Frequency	2,5 GHz
Site	Installation height	Not applicable
	Number of sectors per site	Not applicable
Site cluster	Number of sites	1
	Cell shape	Not applicable
Antenna	Type	Square-shaped array antenna with 8×8 elements. Impact of array size analysed.
	Dimension of the array antenna panel	$4\lambda \times 4\lambda$ to $8\lambda \times 8\lambda$ where λ is the wavelength
	Maximum gain in the main lobe	23 dBi to 28 dBi
	Horizontal half-power beamwidth (HPBW-H)	7° to 12,5° (central beam)
	Vertical half-power beamwidth (HPBW-V)	7° to 12,5° (central beam)
	Beam steering range (azimuth)	100°
	Beam steering range (elevation)	40°
Radiating element	Gain	10 dBi
	Horizontal half-power beamwidth (HPBW-H)	67°
	Vertical half-power beamwidth (HPBW-V)	40°
Equipment transmitter	Rated maximum transmitted power	Results are independent of this parameter since only a relative relationship between input power and percentage of the radiated field is considered in the study
	Rated maximum transmitted EIRP	Results are independent of this parameter since only a relative relationship between input power and percentage of the radiated field is considered in the study
System simulations	Beamforming type	Grid of beams
	Channel model / traffic load	Results are independent of this parameter since only a relative relationship between input power and percentage of the radiated field is considered in the study
	Number of simultaneously served UEs	Statistical model (triangular distribution)

Type	Simulation model parameters	Specification
	UE spatial distribution law	Models corresponding to urban and rural installation scenarios
	UE indoor/outdoor ratio	Not applicable
	UE service duration	Statistical model
	Model operation duration	Not applicable
	Time averaging period	Results are independent of this parameter since only a relative relationship between input power and percentage of the radiated field is considered in the study
	Contributions from adjacent and other beams (from IEC 62232:2017, Annex F.10)	Included

The outcome of the modelling studies is summarized in Figure 19.



NOTE A triangular distribution function for the parameters was used.

Figure 19 – Relationship between additional power reduction factor and CDF as a function of number of beams (number of incoherent areas)

The simple approach makes it possible to determine the additional power reduction factor for antennas with an even larger number of elements.

13.2.6 Lessons learned

Modelling studies can be used for the evaluation of the actual maximum transmitted power or EIRP of a BS. For the next edition of IEC 62232, it should also be considered to:

a) add the new terms and definitions including those specified in Clause 2, and a description of the new parameters to be used for implementing actual maximum approaches in 4G and 5G;

b) add general requirements to evaluate the CDF of the normalized transmitted power or EIRP, to derive the actual maximum transmitted power or EIRP and the corresponding RF compliance boundary;

c) consider measurement validation and sensitivity analysis of modelling study results with input parameters variations;

d) add equations for technology duty cycles (LTE-TDD, LTE-FDD and 5G);

e) define how to build simulation scenarios to be considered in modelling studies to address compliance with exposure guidelines and align simulation models with 3GPP guidelines for conducting channel model simulations for 4G and 5G (e.g. using [6] and [7];

f) add general requirements to enforce the implementation of RF exposure compliance boundaries based on the actual maximum power or EIRP and ensure this is not exceeded during field operations of the BS;

g) add recommendations about the implementation of actual maximum approaches with all BS types.

13.3 Measurement studies on operational sites with BS using mMIMO

13.3.1 Guiding principles

Measurement studies are performed to assess the RF exposure in the vicinity of mMIMO BS installed on operational sites or site clusters including trials. Due to the high variability of the transmitted signal in azimuth, elevation and time, statistical analysis of the transmission parameters of the base station is recommended. According to B.5.1 (IEC 62232:2017), actual maximum transmitted power can be obtained from network-based measurements, gathering information from either a single cell, or a cluster of cells deployed across a large geographical area and performing a statistical analysis.

The purpose of 13.3 is to build a stable and coherent framework that can be used to evaluate the actual maximum RF exposure in the surrounding locations.

The general process to conduct experimental studies on mMIMO site or site cluster is as follows.

a) Define the investigation area, the list of relevant transmitters impacting RF exposure and their parameters, including the key system parameters for the technology or technologies under investigation(s).

b) Perform network-based measurements using BS counters (see 13.3.3.3) of relevance for the RF exposure assessments. This includes azimuth, elevation, time and in-situ RF exposure measurements, provided the purpose of the statistical analysis is to extrapolate field measurements to the actual maximum transmitted power.

c) Derive statistical distribution of the transmitted power and evaluate the actual maximum RF exposure parameters within the investigation area.

13.3.2 Measurement campaign parameters

Before starting RF exposure measurements in the vicinity of a BS site or site cluster, it is recommended to collect general information that can impact the outcome of the RF exposure assessment. Table 15 provides the relevant parameters.

Table 15 – Measurement campaign parameters for conducting RF exposure assessment of a massive MIMO site or site cluster

Type	Measurement campaign parameters	Example(s)	Proposed for inclusion in next edition of IEC 62232
General	Investigation purpose	General public exposure or occupational exposure or validation of modelling studies or other	
	Investigation area	Geographical description of the area under investigation	
	Investigation time	From Day 1 to Day 2	
	Technology(ies) under investigation	LTE-TDD / 5G NR	

Type	Measurement campaign parameters	Example(s)	Proposed for inclusion in next edition of IEC 62232
	Technology use case	Mobile broadband	
	Environment type	Urban or sub-urban	
Per technology	Technology	5G NR TDD	
	Technology duty cycle	0,75	x
	Frequency	3,6 GHz (in 3GPP Band 42)	
	Number of sites in the experiment	1	
Per site/cluster	Address	Street, City, Country	
	Position (GPS or equivalent)	N:48.812476; E2.361383	
	Installation height	10 m	
	Number and azimuth of sectors (cells) per technology/frequency	3 sectors using azimuth 30° (sector 1), 150° (sector 2) and 270° (sector 3)	
Per antenna	Type	2D array antenna with 32 cross polarized radiating elements: 4 columns × 8 rows	
	Dimension	30 cm × 60 cm	
	Maximum gain in the main lobe	24 dBi	
	Horizontal half-power beamwidth (HPBW-H)	12° (at 3 dB)	
	Vertical half-power beamwidth (HPBW-V)	8° (at 3 dB)	
	Beam steering range (azimuth)	90° (at 3 dB)	x
	Beam steering range (elevation)	40° (at 3 dB)	x
	RF compliance boundary	According to IEC 62232	
Equipment transmitter	Rated maximum transmitted power	100 W (50 dBm)	
	Rated maximum transmitted EIRP	74 dBm	
RF exposure	RF exposure modelling on the investigation area (if available)	According to IEC 62232:2017	
	Field measurement types	In-situ, Case A and Case B as specified in 6.3.2.2 and 6.3.2.3 (IEC 62232:2017)	
	Measurement equipment	Equipment name, frequency range, accuracy, etc.	
	Base station counters	Averaged DL transmitted per cell, connected users per cell, etc.	
	Counter time averaging period	15 min	
	Specific requirements	For example, indicate here if process was used to ensure there is at least a communication on the site towards the point of investigation	

13.3.3 Experiment process

13.3.3.1 General description

The experimental process consists of performing the RF exposure assessment in the investigation area in accordance with IEC 62232. In parallel, base station counters are collected in order to assess impact of time variations due to traffic load on RF exposure or provide other relevant information for consistency checks.

13.3.3.2 In-situ RF exposure assessment

The general process developed for in-situ RF exposure measurements is described below.

a) Perform a site analysis using broadband measurement as specified in 6.3.2.2 (IEC 62232:2017) by scanning the area of investigation at 1,5 m height in order to identify the position of maximum exposure (a test device can be used to ensure that there is traffic towards the location of measurements).

b) Identify if there are other locations of specific interest in the investigation area, such as places where people can stay for a long period of time (e.g. a period of time exceeding the EMF averaging time).

c) At the location of maximum exposure (see step a)) and other specific locations (see step b)), perform spatial averaging measurements according to IEC 62232:2017 requirements using Case A broadband type measurements (minimum) as specified in 6.3.2.2 (IEC 62232:2017) or Case B comprehensive exposure evaluation as specified in 6.3.2.3 (IEC 62232:2017) to account for the contribution of all relevant RF sources.

d) For the case where the purpose of the RF assessment is to evaluate the maximum RF exposure conditions taking into account traffic and transmitted power variations (the measurement points in step c)), derive the actual maximum RF exposure from counter data and the CDF of transmitted power (see 13.3.3.3) during the measurement period.

More considerations for addressing the variation of beam directions over time in the next edition of IEC 62232 can be found in 13.3.5.

13.3.3.3 Base station counters

Various counters of quantities measured on the BS are relevant for the analysis of the transmitted power of massive MIMO base stations (counter naming can differ depending on the base station vendor), such as:

a) average downlink RF transmitted power: this counter monitors the RF power transmitted by the antenna (i.e. the sum of the real RF transmitted power from all individual radiating elements) and delivers the average value for the reporting interval;

b) average number of paired layers: this counter monitors the number of simultaneous multiuser-MIMO layers that are set by the mMIMO system in every transmission slot (i.e. the number of simultaneous beams generated by beamforming) and delivers the average value for the reporting interval. This counter can be delivered on a per-resource block basis; therefore, some post-processing to obtain the average value is needed;

c) average PRB usage index: this counter monitors the ratio of occupied resource blocks in every transmission slot (i.e. the percentage of PRBs that have been allocated to users) and delivers the average value for the reporting interval. This counter allows checking the consistency of the RF transmitted power counter, as power is directly related to the number of PRBs transporting data;

d) average number of active users: this counter monitors the number of active users in every transmission slot (i.e. the number of users that have been allocated with one or more PRBs) and delivers the average value for the reporting interval. This counter allows checking the consistency of the number of beams counter, as the number of paired layers is directly related to the number of allocable users.

The reporting interval for network counters is typically 15 min, although 5 min or 6 min are possible for some vendors' network management system.

When performing statistics on operational networks, it is important to ensure they are taken on a period that is representative of the variability of operations, e.g. considering load variations within a day or a week or other seasonal effects in touristic areas, etc. To obtain statistically relevant results, it is recommended to collect data for a sufficiently long period of time, for example one week per configuration type.

13.3.4 Examples of RF exposure experiments

13.3.4.1 Measurement campaign parameters

As examples of the applicability of the previously described procedure, six experiments have been carried out using existing mMIMO testbeds in LTE-TDD 2600 band in different environments and under different traffic profiles. The measurement campaign parameters are summarized in Table 16.

Table 16 – Measurement campaign parameters for RF exposure validation of several massive MIMO sites and site clusters

Type	Measurement campaign parameters	Example(s)	Proposed for inclusion in next edition of IEC 62232
General	Investigation purpose	Validation of modelling studies	
	Investigation area	Urban neighbourhood | Suburban campus | Indoor stadium | Motor circuit | Urban festival | Suburban train station	
	Experiment number and investigation time in parenthesis	#1 (1 month) | #2 (1 month) | #3 (1 week) | #4 (3 days) | #5 (5 days) | #6 (1 day)	
	Technology(ies) under investigation	LTE-TDD	
	Technology use case	Mobile broadband	
	Environment type	Urban | Suburban | Indoor | Suburban | Urban | Suburban	
Per technology	Technology	LTE TDD	
	Technology duty cycle	0,75	
	Frequency	2 600 MHz (in 3GPP Band 38)	
	Number of sites in the experiment	8 | 1 | 1 | 6 | 1 | 1	
Per site/cluster	Address	Madrid | Newbury | Istanbul | Silverstone | Albacete | Bristol	
	Position (GPS or equivalent)	(Several)	
	Installation height	(Several)	
	Number and azimuth of sectors (cells) per technology/frequency	1 cell per site, several azimuths	
Per antenna	Type	2D array antenna with 64 cross-polarized radiating elements: 8 columns × 8 rows	
	Dimension	86 cm × 52 cm	
	Maximum gain in the main lobe	24 dBi	
	Horizontal half-power beamwidth (HPBW-H)	15° (at 3 dB)	
	Vertical half-power beamwidth (HPBW-V)	10° (at 3 dB)	
	Beam steering range (azimuth)	±30° (at 3 dB)	x
	Beam steering range (elevation)	±15° (at 3 dB)	x
	RF compliance boundary	According to IEC 62232	
Equipment transmitter	Rated maximum transmitted power	50 W | 40 W | 80 W | 60 W | 80 W | 80 W	
	Rated maximum transmitted EIRP	71 dBm | 70 dBm | 73 dBm | 72 dBm | 73 dBm | 73 dBm	

Type	Measurement campaign parameters	Example(s)	Proposed for inclusion in next edition of IEC 62232
RF exposure	RF exposure modelling on the investigation area (if available)	According to IEC 62232	
	Field measurement types	None (only BS counters)	
	Measurement equipment	None (only BS counters)	
	Base station counters	Average DL RF transmitted power; average number of paired layers; average PRB usage index; average number of active users	
	Counter time averaging period	15 min | 5 min | 1 s	
	Specific requirements	Ensure users are connected and served normally by the studied cells	

13.3.4.2 Measurement collection

The four counters specified in 13.3.3.3 have been used. These values are time-averaged over the reporting interval. The reporting interval for network counters was 15 min in most cases, though data collection at 5 min and 1 s intervals was performed for benchmarking purposes. In all cases, the reporting interval is several orders of magnitude longer than the transmission frame. Therefore, the technology duty cycle factor is included in the counter and shall not be added to the counter itself.

The maximum value achievable by the average downlink RF transmitted power counter is the time-averaged maximum transmitted power, specified in Equation (6) as follows:

$$P_{\text{TXMTA}} = P_{\text{TXM}} \times F_{\text{TDC}} \tag{6}$$

where

P_{TXMTA} is the time-averaged maximum transmitted power in downlink (deterministic factor);

P_{TXM} is the maximum transmitted power in downlink (deterministic factor);

F_{TDC} is a scaling factor representing the technology duty cycle of the signal (deterministic factor).

13.3.4.3 Results of the measurement study

The processing of measured data was carried out in three stages. Data consistency was checked: RF transmitted power data is correlated with PRB usage data while number of paired layers is correlated with the number of users. Afterwards, average power per beam was obtained by dividing each RF transmitted power sample by each corresponding number of beams per sample. Then, a statistical analysis on the power per beam was performed.

Figure 20 shows a statistical analysis performed using one-month counter logging from a small sample of eight cells using the same 3GPP Band 38 mMIMO antenna models in Madrid (see experiment #1 in Table 16). The environment is an urban scenario, with low traffic conditions. Results include only the 15 min averaged RF transmitted power with no further correction due to beam distribution; therefore, this is an overly conservative case.

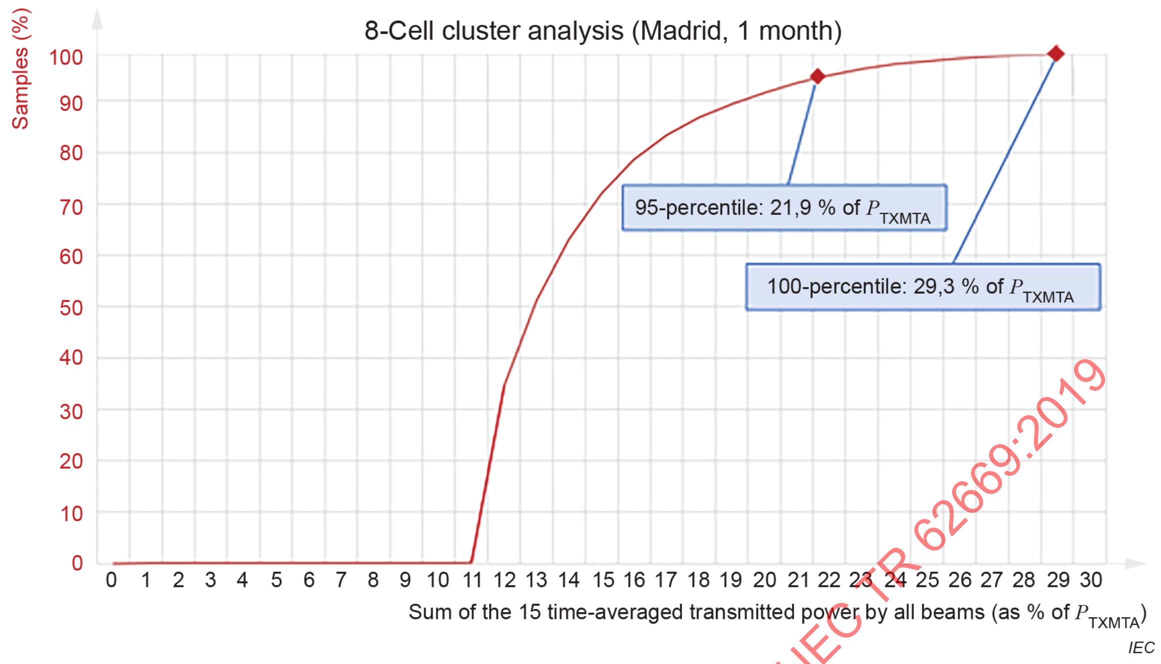


Figure 20 – CDF of measurement on 8-cell cluster (experiment #1)

The actual maximum power can be determined from the CDF on Figure 20, using a 100th percentile (for a small sample of cells) or using 95th percentile (for a larger sample of cells) provided that the operator is implementing tools to ensure this is not exceeded. The actual maximum EIRP ($EIRP_{AM}$) and related values derived from this study are provided in Table 17. For example, the actual maximum EIRP using the 95th percentile approach is calculated with Equation (7), which is derived from Equation (1) and Equation (3), considering the base station configuration parameters shown in Table 16 as follows:

$$EIRP_{AM} = P_{TXM} \times F_{TDC} \times G_{MLB} \times F_{PR} = 50 \times 0{,}75 \times 10^{2{,}4} \times 0{,}22 \text{ (W)} \quad (7)$$

where

P_{TXM} is the rated maximum transmitted power configured by the operator (50 W);

G_{MLB} is the antenna gain in the main lobe (24 dBi);

F_{TDC} is the technology duty cycle of the signal (0,75);

F_{PR} is derived from the 95th percentile of the CDF shown in Figure 20 (0,22).

Table 17 – Actual maximum values for experiment #1

Parameter	Value	
	Using the 100th percentile approach	**Using the 95th percentile approach (for larger sample)**
Power reduction factor	0,29	0,22
Actual max. EIRP (W) from Equation (3)	2 730 W	2 070 W
Actual max. EIRP (dBm)	64,4 dBm	63,2 dBm
D_f (m) from 6.1 (IEC 62232:2017)	4,7 m	3,5 m
D_s (m) from 6.1 (IEC 62232:2017)	1,3 m	1,2 m

Experiment #5 (see Table 16) corresponds to a one-week analysis on a single Band 38 mMIMO hotspot site during an extremely high-traffic event. The statistical analysis of the 15 min averaged transmitted power per beam is shown in Figure 21 and the actual maximum EIRP and related values are provided in Table 18.

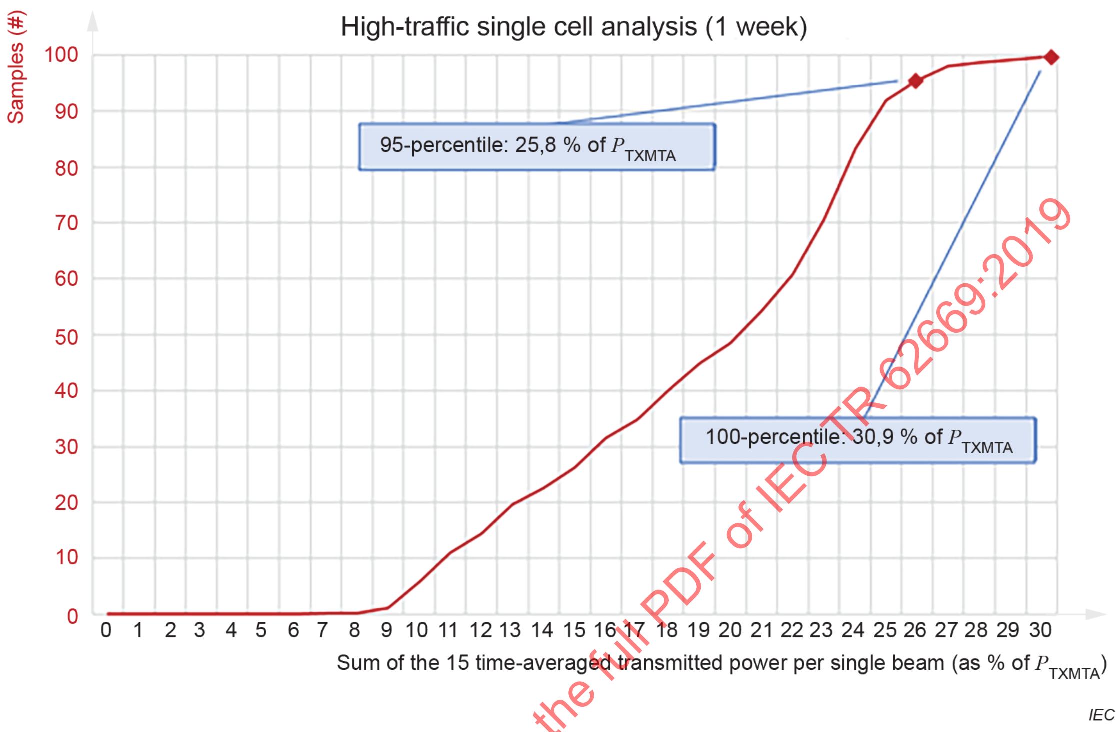


Figure 21 – CDF in high-traffic conditions (experiment #5)

In Table 18, for example, the actual maximum EIRP using the 95th percentile approach is calculated with Equation (7) considering the base station configuration parameters shown in Table 16, as follows:

$$\text{EIRP}_{\text{AM}} = 80 \times 0{,}75 \times 10^{2{,}4} \times 0{,}26 \text{ (W)}$$

Table 18 – Actual maximum values for experiment #5

Parameter	Value	
	Using the 100th percentile approach	**Using the 95th percentile approach (for larger sample)**
Power reduction factor	0,31	0,26
Actual max. EIRP (W) from Equation (3)	4 670 W	3 920 W
Actual max. EIRP (dBm)	66,7 dBm	65,9 dBm
D_f (m) from 6.1 (IEC 62232:2017)	6,1 m	5,6 m
D_s (m) from 6.1 (IEC 62232:2017)	1,7 m	1,6 m

The configurations and outcome for all the six experiments referenced in Table 16 are summarized in Table 19.

Table 19 – Summary of actual maximum power results based on measurements from different sites and clusters

Experiment number	Testbed environment	User mobility	Traffic profile	No. of cells	Measurement period	Power reduction factor using a 100th percentile approach for the actual maximum power	Power reduction factor using a 95th percentile approach for the actual maximum power
#1	Urban neighbourhood	High	Low	8	1 month	0,29	0,22
#2	Suburban campus	High	Low	1	1 month	0,27	0,22
#3	Indoor stadium	Low	High	1	1 week	0,27	0,17
#4	Motor circuit	Low	Low	6	3 days	0,26	0,18
#5	Urban festival	Low	Extremely high	1	5 days	0,31	0,26
#6	Suburban train station	High	Low	1	1 day	0,27	0,20

13.3.5 Lessons learned

With the introduction of massive MIMO systems, specific requirements will likely need to be introduced in the next edition of IEC 62232 to take into account the variation of beam directions over time.

Different measurement configurations could be considered, such as using a dedicated test device to force a fixed beam towards the evaluation point or taking multiple evaluations with different beam orientations configured at the BS level or taking measurement at the point of investigation without beam forcing. These could depend on the purpose of the measurements (e.g. determining compliance assessment with applicable exposure limits and regulations or collecting RF exposure data). TDD mode as well as device used to orient the beam will also add a constraint on measurement. The proposed test protocol can also consider parameters such as transmitted file size, type, duration and repetition. Recording the time of measurements is important in order to derive the appropriate correction factors from counter statistics.

Measurement studies can be used for the evaluation of the actual maximum transmitted power or EIRP of a BS. For the next edition of IEC 62232, it should also be considered to:

a) add new terms and definitions;
b) add the requirements for base station counters (content, name, duration, averaging time, …) using reference to existing standards (e.g. 3GPP) where relevant;
c) add an experimental process to ensure the beam configuration is appropriate to assess the RF exposure at the point of investigation during field measurements (e.g. using a test device to focus the beam on the evaluation point or using specific BS test modes allowing to focus the beam on the evaluation point or defining a method to get the radiated power on the selected beam);
d) add the post processing formulas to derive actual maximum RF exposure from field measurements and CDF of the normalized transmitted power;
e) add in-situ RF exposure assessment requirements to take into account specificities of mMIMO and 5G, such as beam steering mechanisms using a device or BS feature to focus the beam towards the evaluation point or away from the evaluation point, depending on the purpose of the assessment;
f) add a method for evaluating an indicator of mean exposure, for example during a day;
g) add a method for evaluating the extrapolation factors from field measurements;
h) extend the implementation of actual maximum approaches to all types of BS;
i) clarify content and definition of the "Site Analysis".

13.4 Configurations with multiple transmitters

13.4.1 Guiding principles for configurations with multiple transmitters

In realistic exposure scenarios, it is likely that RF exposure is generated by multiple independent transmitters. This occurs where multiple operators and/or transmitters operating on multiple frequencies are on the same site. The probability that multiple independent transmitter systems are delivering the actual maximum RF exposure on the same point at the same time is lower than for one single transmitter.

The proposed approach, which is applicable to either measurement or modelling, is to:

a) derive a Beta distribution law from the CDF of the normalized transmitted power by a transmitter that has been obtained either by simulations or measurements;

b) calculate random combinations and derive the CDF resulting from multiple independent transmitters in the same direction;

c) derive the power combination factors applicable to the actual transmitted power and other relevant percentiles as specified in 13.4.

13.4.2 Rationale

Several statistical distributions can be used to represent the random variations of a quantity. When dealing with power density, it is recommended to look for positive distribution having a finite support. The Beta distribution, introduced by Karl Pearson in the early 1900s, has a positive and a finite support and its shape is fully controlled by two parameters.

The Beta function chosen for conducting the statistical analysis in 13.4 has been derived from CDFs obtained with modelling case study B (see 13.2.4 and [35]). It has a support [0 1] and shape control set at 2 and 15. It provides a normalized transmitted power of 0,35 for the 99th percentile and 0,26 for the 95th percentile. Detailed investigation of such combinations can be found in [37]. The complete CDF is shown in Figure 22 and the quantiles are listed in Table 20.

Table 20 – Quantiles of the reference Beta distribution used to assess power combination factors

Percentiles	5 %	25 %	50 %	75 %	95 %	99 %
P_{DLN}	0,022	0,060	0,102	0,159	0,264	0,348

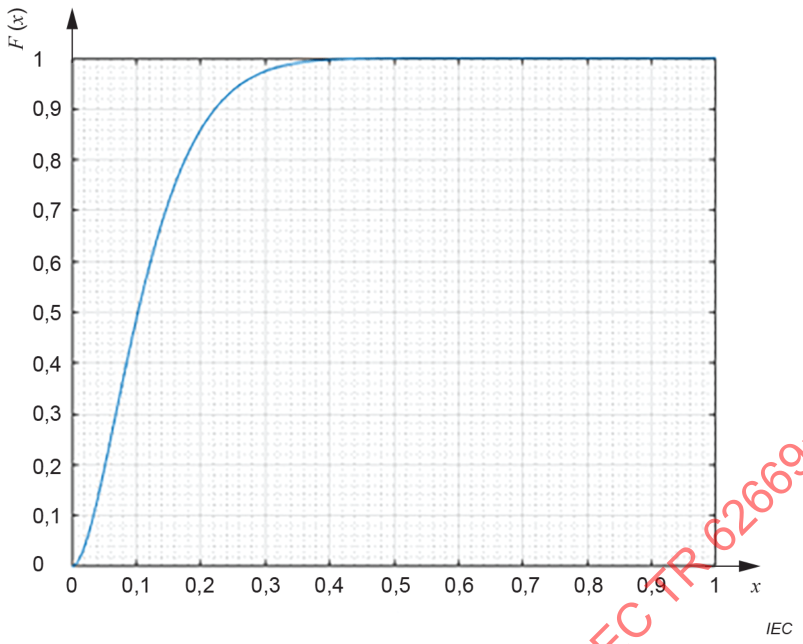


Figure 22 – CDF of the reference Beta distribution used to assess power combination factors

The resulting CDF for the combination of two independent transmitters having the same CDF is shown in Figure 23.

NOTE The validity of this assumption needs to be confirmed for multi-technology systems with cooperation algorithms used to serve a UE or carrier aggregation.

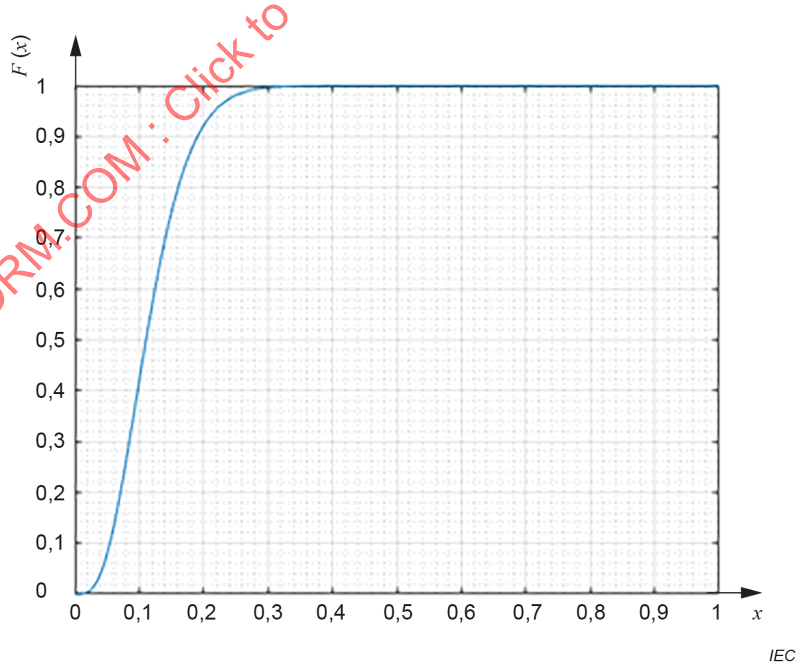


Figure 23 – CDF resulting from the combination of two independent transmitters having the reference Beta distribution

The analysis has been performed for up to five transmitters. The resulting percentiles are provided in Table 21.

Table 21 – Percentiles resulting from the combination of 2 to 5 independent transmitters having the reference Beta distribution

Percentiles	5 %	25 %	50 %	75 %	95 %	99 %
1 transmitter (reference)	0,02	0,06	0,10	0,16	0,26	0,35
2 transmitters	0,04	0,08	0,11	0,15	0,22	0,27
3 transmitters	0,05	0,09	0,11	0,15	0,20	0,24
4 transmitters	0,06	0,09	0,11	0,14	0,19	0,22
5 transmitters	0,07	0,09	0,12	0,14	0,18	0,21

13.4.3 Power combination factors applicable to configurations with multiple transmitters

The outcome of the statistical analysis presented in 13.4.2 shows that a power combination factor can be applied to the actual maximum transmitted power and other relevant percentiles. Examples of power combination factors are provided in Table 22.

Table 22 – Power combination factors applicable to the normalized transmitted power CDF in case of combination of multiple independent identical transmitters

Percentiles	5 %	25 %	50 %	75 %	95 %	99 %
1 transmitter (reference)	1,00	1,00	1,00	1,00	1,00	1,00
2 transmitters	1,91	1,30	1,08	0,94	0,82	0,77
3 transmitters	2,46	1,43	1,11	0,91	0,75	0,68
4 transmitters	2,82	1,50	1,12	0,89	0,71	0,63
5 transmitters	3,05	1,55	1,13	0,87	0,67	0,60

One important assumption in the assessment of power combination factors in Table 22 is that all transmitters have the same maximum transmitted power, i.e. the same weight in the statistical combination. If the maximum transmitted power is not the same or if the frequency band is not the same, the weighting in the statistical combination will have to be adapted to take into account the different maximum transmitted powers or/and the relevant reference levels.

Assuming that the combination applies to two independent signals having the same CDF, where one signal is equal to a ratio p of the other, the combination factors can be adjusted as shown in Table 23. The value with p = 1 corresponds to the power combination factor from Table 22.

Table 23 – Power combination factors applicable to two independent transmitters with a ratio p in amplitude

Ratio p between two independent transmitters	Power combination factors					
	Percentiles					
	5 %	25 %	50 %	75 %	95 %	99 %
0,1	1,34	1,09	1,01	0,98	0,95	0,95
0,2	1,55	1,15	1,03	0,96	0,91	0,90
0,3	1,68	1,20	1,04	0,95	0,89	0,86
0,4	1,77	1,24	1,06	0,95	0,87	0,83
0,5	1,81	1,26	1,06	0,94	0,85	0,81
0,6	1,85	1,27	1,07	0,94	0,84	0,80
0,7	1,87	1,28	1,07	0,94	0,83	0,79

Ratio p between two independent transmitters	Power combination factors					
	Percentiles					
	5 %	25 %	50 %	75 %	95 %	99 %
0,8	1,88	1,29	1,07	0,94	0,83	0,78
0,9	1,89	1,29	1,08	0,94	0,82	0,78
1	1,91	1,30	1,08	0,94	0,82	0,77

13.4.4 Lessons learned

Statistical studies show that combination factors can be applied for the evaluation of the actual maximum transmitted power or EIRP of multiple independent sources, either from a single BS using multiple independent carriers or from multiple BS on the same site. This applies to BS with fixed beams or using steerable beam like mMIMO.

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

a) add the new terms and definitions;

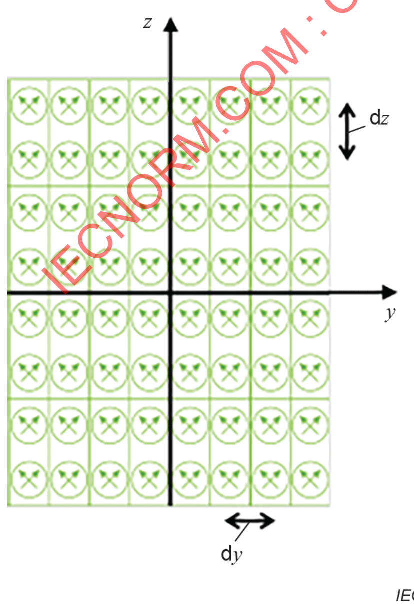
b) add a description of the new parameters and methods to be used for assessing the actual maximum exposure in case of multiple sources;

c) add discussion on the validity of the assumption of independence of transmitters.

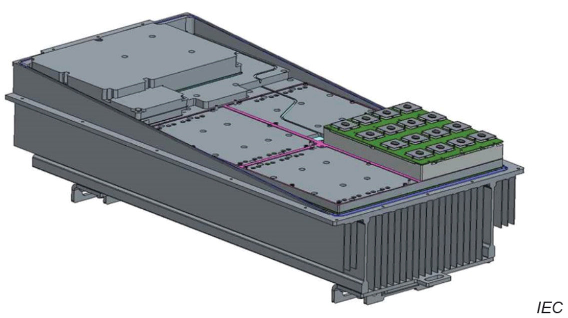
14 Macro BS with massive MIMO product compliance assessment

14.1 General description

This case study describes a product compliance assessment of a 5G radio base station (BS) product employing massive MIMO using methodology specified in IEC 62232:2017. The BS product considered operates in the 3,5 GHz frequency band and consists of 128 transmit/receiver branches. The array antenna consists of four antenna modules with dual polarized antenna elements according to Figure 24.



a) Schematic view of the four antenna modules with cross-polarized antenna elements



b) One antenna module mounted in the BS product

Figure 24 – 5G BS product

The purpose of the assessment is to determine a RF compliance boundary outside of which the radio frequency exposure is below the ICNIRP general public and occupational exposure limits [8] provided in Table 24. The evaluation is based on numerical power density calculations using the spherical far-field formula and considers effects of scanning in elevation and azimuth, scan loss and the actual maximum transmitted power.

Table 24 – RF EMF exposure limits relevant for the product compliance assessment [8]

5G frequency band (GHz)	EMF exposure limit (W/m^2)	
	General public	Occupational
3,5	10	50

14.2 Implementation of IEC 62232:2017

14.2.1 Evaluation process

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

The use of basic computations was selected, and the procedures described in 6.1.5.4 (IEC 62232:2017) were used. Using the guidelines of Figure 13 and Table 7 in 8.3 (IEC 62232:2017) and Table A.11 in Clause A.4 (IEC 62232:2017), the spherical formula for power density method was applied.

14.2.2 Methodology

For the equipment under test (EUT), which makes use of a massive-MIMO array antenna, a simple RF compliance boundary in the form of a rectangular box was selected based on the guidelines in 6.1.4 (IEC 62232:2017). The RF compliance boundary is described in terms of the EUT dimensions and the compliance distances in front of, behind, above/below, and to the sides of the EUT according to Figure 25.

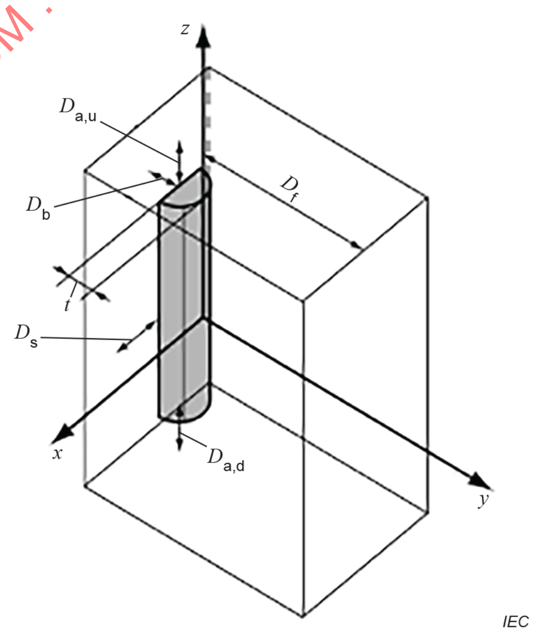


Figure 25 – Box-shaped RF compliance boundary

A requirement of the compliance evaluation is to define the set of conservative BS parameters for a BS under normal use; this requires a detailed analysis specific to the employed technology. A differentiating factor between 5G New Radio (NR) and previous radio access technologies (RATs) is the employed "beam-centric design" which aims to transmit energy in narrow beams towards the directions where it is needed rather than to constantly transmit energy in a wide angular sector. This focusing of energy in different directions will also impact the realistic exposure of 5G BS products. An exposure assessment of a 5G NR system employing massive MIMO based on the traditional approach employed for previous RATs would assume that the maximum power is transmitted in each possible direction for a time-period in the order of minutes, corresponding to the averaging time of the relevant RF exposure limits. This is very unrealistic, if even possible, and would lead to a very conservative RF compliance boundary consistent with the envelope of all possible array excitations/beams, where each beam is transmitting at the maximum transmitted power.

In this product compliance assessment, results were obtained for the actual maximum power as described in Clause B.5 (IEC 62232:2017) and determined according to the methodology described in [33] which is an expansion of the approach in Clause F.10 (IEC 62232:2017). As explained in [33], the actual maximum transmitted power depends on the environment in which the 5G BS will later be installed as this will have an impact on the expected distribution of connected users and thereby on how the time-averaged transmitted power is distributed within the scan range of the array antenna. For this product compliance assessment, an actual maximum transmitted power level of 25 % of the corresponding maximum transmitted power (according to the general principles introduced in 13.1), applicable for the considered array size and both rural and urban environments [33], was selected.

14.2.3 Reporting

Annex H.1 provides the technical details of the site and the numerical parameters used for the assessment and Annex H.2 provides the compliance test report following the requirements of IEC 62232. The modelling 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).

14.3 Technical outcome

The obtained RF compliance boundary dimensions obtained for a conservative actual maximum transmitted power level of 62,9 W including an assumed 1 dB power tolerance taking into account manufacturing dispersion are provided in Table 25.

Table 25 – Dimensions of the box-shaped RF compliance boundary for general public (GP) and occupational (O) exposure for an actual maximum transmitted power configuration

Mode and RF transmitted power for EUT			Dimensions of the box-shaped RF compliance boundary (m)									
			Distance in front of EUT (D_f)		Distance to the side of EUT (D_s)		Distance above EUT ($D_{a,u}$)		Distance below EUT ($D_{a,d}$)		Distance behind EUT (D_b)	
Band	**Rated maximum transmitted power from the EUT**	**Actual maximum transmitted power**	**GP**	**O**	**GP**	**O**	**GP**	**O**	**GP**	**O**	**GP**	**O**
B42 (3 500 MHz)	200 W	62,9 W	11,6	5,2	7,1	3,1	4,0	1,5	4,3	1,8	0	0

NOTE The specified RF compliance boundary width and height values (distance above EUT + distance below EUT) are determined by the RF EMF exposure in the main beam considering effects of applicable scan range. In the vicinity of the EUT, however, the simple box-shaped RF compliance boundary is very conservative. For specific installation scenarios, more accurate product installation compliance assessments can be performed to allow the use of a more accurate RF compliance boundary shape.

Outside of this box the RF exposure is below the exposure limits specified by ICNIRP, see Table 24 and [8].

14.4 Lessons learned

For accurate compliance assessment results, it is very important to properly define the set of conservative BS parameters and provide the actual maximum transmitted power conditions in order to not obtain overly conservative and unrealistic results.

For the next edition of IEC 62232, it should be considered to add guidelines for conducting product compliance assessment of 5G BS using massive MIMO based on the actual maximum approach.

15 Macro site with massive MIMO product installation compliance assessment

15.1 General description

This case study describes a product installation compliance assessment of a base station site in a mobile communications network using the methodology specified in IEC 62232. The site is located on a rooftop in an urban area and consists of a number of base station (BS) products with integrated phased array antennas employing beamforming technology (massive MIMO), all managed by a single network operator. The site operates in multiple bands to offer both larger area geographic coverage, as well as localized services to users. For the purpose of this case study we will assume three of the base stations operate in the 3,5 GHz frequency band and are installed to provide geographic area coverage in all directions around the site. Then another base station operates in the 28 GHz band and only provides local coverage to the area in line of sight (LoS) in front of the antenna. For both operating bands, the massive MIMO equipment works under a TDD scheme, due to the simpler and more precise channel estimation procedures needed for accurate beamforming. This means that only a fraction of the total time considered for exposure assessment is actually used for DL transmission. The operational frequencies used in this case study do not imply any limitation to the applicability of the assessment procedures described within the document; therefore, this methodology can be considered valid for other massive MIMO sites, including those operating in higher and lower frequencies (e.g. 2 600 MHz).

This evaluation is based on computational methods and takes into account the actual maximum transmitted power of the array antennas. For this case study we will assume that the site is situated in a European country that uses ICNIRP based limits for general public [8] and occupational exposure as specified in EU Council Recommendation 1999/519/EC [38] and EU Directive 2013/35/EU [39]. No other radio sources are installed on the same rooftop or on neighbouring roofs, meaning that the RF exposure from ambient sources is not relevant (i.e. the contributions to the total exposure are less than 5 % of the limits) and do not need to be considered in the compliance assessment of this site.

Figure 26 shows an outline of the site and Table 26 gives the relevant EMF exposure limits for general public and occupational exposure that have been used for the compliance assessment.

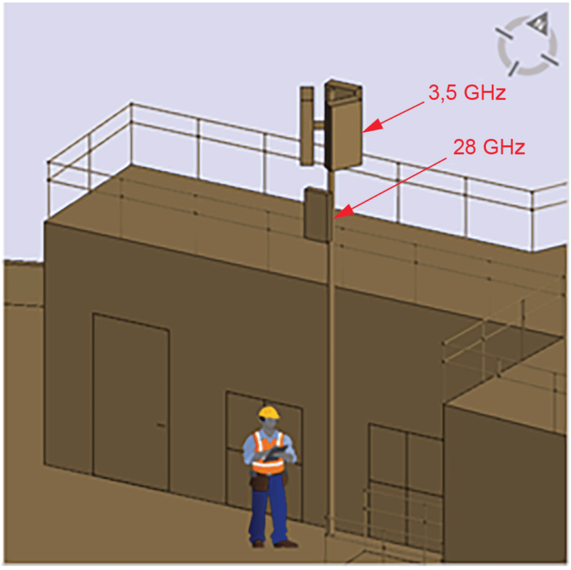


Figure 26 – Outline of the 5G site

Table 26 – RF EMF exposure limits relevant for the compliance assessment

5G frequency band (GHz)	**EMF exposure limit** (W/m^2)	
	General public	**Occupational**
3,5	10	50
28	10	50

15.2 Implementation of IEC 62232:2017

15.2.1 Evaluation process

This product installation compliance assessment follows the procedure specified in 6.2 (IEC 62232:2017). According to this procedure, the simplified evaluation option described in 6.2.4 (IEC 62232:2017) was deemed not to be applicable for this site since all the installation criteria specified in Table 2 (IEC 62232:2017) for the relevant class (E+) were not met. On the other hand, based on calculations using the equations in 6.2.5 (IEC 62232:2017) and Equation (6.6) (IEC 62232:2017), and applying the maximum vertical scan angle of 23° as the antenna down-tilt, it was determined that the public can access the assessment domain boundary (ADB) and therefore, a comprehensive evaluation is necessary.

For this evaluation, the use of computations was selected, and the procedures described in 6.2.7 were used. Following the guidelines of Figure 13 and Table 7 in 8.3 (IEC 62232:2017) and Tables A.11 and A.12 (IEC 62232:2017), it was decided to apply the method "Synthetic model and ray tracing algorithms" specified in B.4.4.1 (IEC 62232:2017).

15.2.2 Methodology

Data for the product installation was collected according to 6.2.3 (IEC 62232:2017). In this product installation compliance assessment, results were obtained for the actual maximum as described in B.5 (IEC 62232:2017) and determined according to the methodology described in [33], which is an expansion of the approach in F.10 (IEC 62232:2017) to take into account the actual spatial distribution of users. This methodology is most suitable for the beamforming capabilities of massive MIMO antennas. For a compliance evaluation, the requirement from the Radio Equipment Directive 2014/53/EU [40] is to take into account all intended operating conditions and the reasonably foreseeable conditions. This requires a detailed analysis specific to the employed technology and in this case, the antenna technology presents some particular features.

For the scope of this product installation assessment, the selected approach is using the actual maximum transmitted power value as specified in 13.1, in order to obtain feasible and accurate results when calculating exposure at each possible steering direction of the main beam.

As explained in [33], the actual maximum transmitted power depends on the environment in which the base station is installed as this will have an impact on the expected distribution of connected users and thereby on how the time-averaged transmitted power is distributed within the scan range of the array antenna. For this product installation compliance assessment, given the considered array size and the urban environment, a conservative actual maximum transmitted power level of 25 % of the corresponding maximum transmitted power was selected, as recommended in [33]. Additional results obtained from real measured transmitted power data (shown in 13.3) support the selection of this value as a realistic conservative figure. It is worth noting that this conservative actual transmitted power also takes into account that the fraction of time devoted for DL transmission in TDD schemes is less than the total time considered for exposure evaluation.

15.2.3 Reporting

Annex I provides the technical details of the site, the EUT and the evaluation procedure used for the assessment. Clause I.6 provides the compliance test report following the requirements of IEC 62232. The modelling uncertainty was calculated according to 6.2.8 and Clause 9 (IEC 62232:2017) and the results were reported according to 6.2.9 and Clause 10 (IEC 62232:2017).

15.3 Technical outcome

The compliance boundaries for the general public and for workers have been obtained under the initial assumption of a conservative actual maximum transmitted power level of 25 % of the maximum transmitted power for all four base stations installed on the site. A justification for this assumption can be found in [33]. Additional supporting evidence can be obtained from actual massive MIMO sites in live operation (such as the ones detailed in 13.3). Then, the actual maximum power was used to evaluate the exposure of the main user beam for every possible steering direction.

Obtained results for the compliance boundaries are provided in Figure 27 and Figure 28.

Dimensions in metres

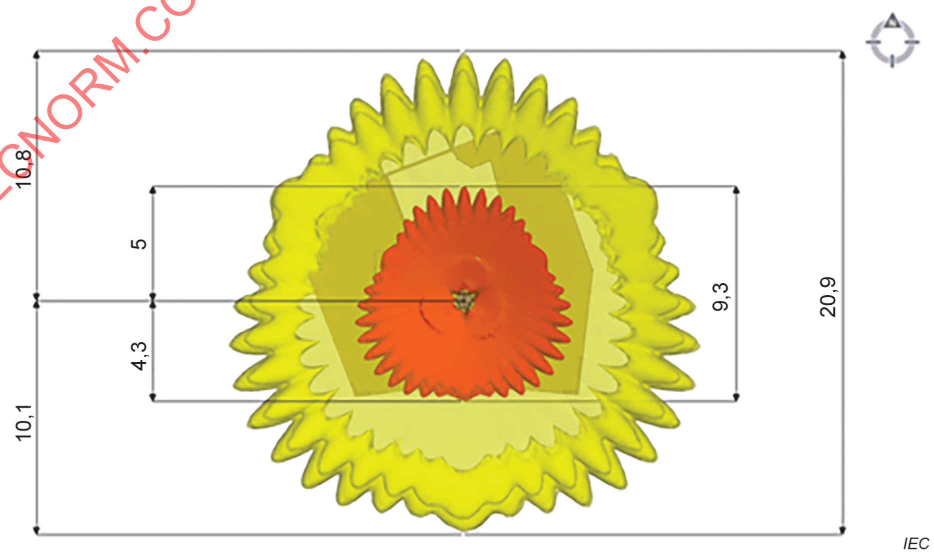


Figure 27 – Top view of the exclusion zones (red: occupational, yellow: general public)

Dimensions in metres

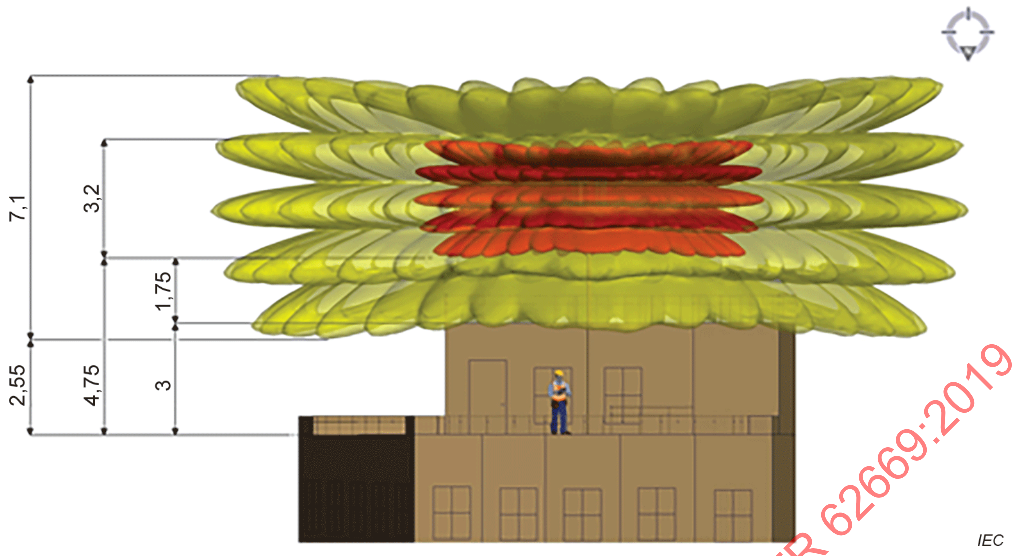


Figure 28 – Side view of the exclusion zones (red: occupational, yellow: general public)

As seen in Figure 27 and Figure 28, the RF EMF exposure from the site considering all possible steering directions of the beams is below the ICNIRP general public limit [8] in the entire area accessible for the general public. The distance from the floor to the lowest point of the RF compliance boundary (exclusion zone) is 2,55 m, which is above head height. Three metres above the accessible floor is an elevated level with restricted access. The RF compliance boundary for workers extends to 1,75 m above the elevated floor level in some areas of the elevated structure, see Figure 28. Therefore, the operator has introduced access restrictions to ensure that workers cannot enter this area. Consequently, the evaluation shows that the base station installation is compliant with the applicable RF EMF exposure limits.

15.4 Lessons learned

For accurate compliance assessment results, it is very important to properly define the set of conservative BS parameters. For BS products using massive MIMO, the assessments can be made for actual maximum transmitted power conditions in order to not obtain overly conservative and unrealistic results (see Clause 13).

As explained in 13.2, the initial assumption of the conservative value for the actual maximum transmitted power was based on the theoretical work found in [33] and on the analysis of real measurements presented in 13.3. This assumption can be considered valid for massive MIMO sites with features similar to the ones of the site under study, even for different operational frequencies. Moreover, the assessment procedure detailed in this document can be considered to be applicable to sites with slightly different massive MIMO configurations. This could include scenarios with different array sizes, operating bandwidths, frequency ranges, and power levels.

For the next edition of IEC 62232, it should be considered to add guidelines for conducting product installation compliance assessment of 5G BS using massive MIMO based on the actual maximum approach (see Clause 13) using either modelling studies or measurement studies.

16 Small cell products at millimetre-wave frequency using massive MIMO

16.1 General description

These case studies describe the product installation and in-situ compliance assessment of a 5G small cell with a massive MIMO antenna using methodology specified in 6.2 and 6.3 (IEC 62232:2017).

16.2 Indoor product installation case study

16.2.1 Product configurations

A 5G TDD small cell with massive MIMO antennas transmitting at 27 GHz was installed at an indoor test and innovation laboratory. A picture of the site is provided in Figure 29.

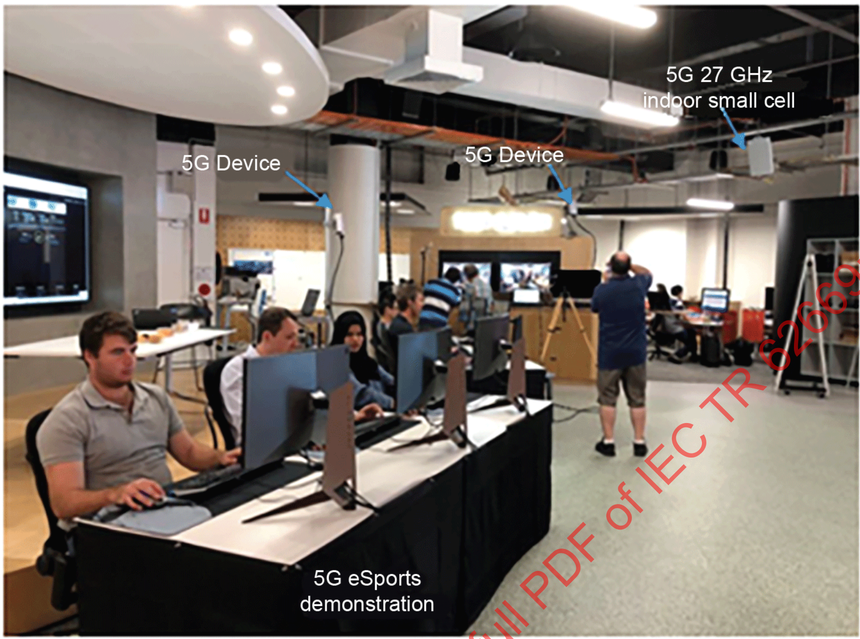


Figure 29 – Indoor site with 5G small cell product at millimetre-wave frequency

The equipment under test includes an indoor small cell BS product that is installed 3 m above ground level which is accessible to all people. The small cell has two power configurations:

- power configuration 1: full power test mode (48 dBm EIRP);
- power configuration 2: demonstration mode (38 dBm EIRP).

This is the installed configuration for the 5G indoor trials and demonstrations The EIRP of Configuration 2 is 10 dB lower than Configuration 1 in order to address indoor coverage area and good quality signal. This is also required to avoid overloading the system.

16.2.2 Implementation of IEC 62232:2017

16.2.2.1 Evaluation process

This product installation compliance assessment follows the procedure as specified in 6.2 (IEC 62232:2017) and specifically the simplified evaluation process described in 6.2.4 (IEC 62232:2017). Table 2 (IEC 62232:2017) specifies the product installation classes where a simplified evaluation process is applicable (based on ICNIRP general public limits [8]).

16.2.2.2 Methodology

Depending on the ongoing activities in the laboratory, the TDD factor varied between 50 % and 96 %. In this assessment a conservative TDD factor of 96 % was chosen for outdoor locations.

The indoor small cell installation in demonstration mode is classed as E10 (< 10 W or 40 dBm EIRP) and therefore meets the requirements for the simplified installation. For the E10 class, the simplified installation guide states: "The product is installed according to instructions from the manufacturer and/or entity putting into service and the lowest radiating part of the antenna(s) is at a minimum height of 2,2 m above the general public walkway."

In summary, the indoor small cell is located away from public access and operates at a low power level, therefore meeting the requirements of 6.2.4 (IEC 62232:2017) and no further assessment is required. The indoor small cell installation in full power test mode is classed as E100 (< 100 W or 50 dBm EIRP) and meets the requirements for the simplified installation under the following conditions.

The product is installed according to instructions from the manufacturer and complies with the following criteria:

a) the lowest radiating part of the antenna(s) is at a minimum height of 2,5 m above the general public walkway;

b) the minimum distance to areas accessible to the general public in the main lobe direction is D_m = 0,7 m as provided by the manufacturer;

c) there is no pre-existing RF source with EIRP above 10 W installed within a distance of 3,5 m ($5D_m$) in the main lobe direction (as determined by considering the half power beam width) and within 0,7 m (D_m) in other directions.

For this product installation there is no need for further assessments.

16.2.2.3 Reporting

Annex J provides the test reports that have been prepared in accordance with the requirements of 6.2.9 and Clause 10 (IEC 62232:2017).

16.2.3 Technical outcome

Using the simplified evaluation process of 6.2 (IEC 62232:2017), the small cell product installation, for both configurations, has been found to be compliant with the ICNIRP general public exposure limits [8].

16.2.4 Lessons learned

The description on how to apply the simplified installation criteria described in Table 2 (IEC 62232:2017) for E100 and E+ can be made clearer, possibly by adding a flow chart.

16.3 In-situ measurement case study

16.3.1 Product configurations

A 5G small cell was installed on a 44 m radio tower, see Figure 30.

Figure 30 – Outdoor site with 5G small cell product at millimetre-wave frequency installed on a 44 m radio tower

The objectives of these in-situ measurements as per 6.3.1 (IEC 62232:2017) are:

a) to obtain RF exposure data inside the 5G laboratory from the indoor 5G small cells for information purposes for workers and the visiting public;

b) to obtain RF exposure data in the local area surrounding the outdoor small cells to provide information to the local community and stakeholders on 5G exposure levels;

c) to provide a comparison of the 5G RF exposure levels to other mobile and radio communication sources.

16.3.2 Implementation of IEC 62232:2017

16.3.2.1 Evaluation process

This in-situ assessment follows the procedure as specified in 6.3 (IEC 62232:2017) except for the spatial averaging requirement where the measurement height was specified by the customer. Specifically, this is the comprehensive RF exposure evaluation (Case B) in 6.3.2.3 (IEC 62232:2017). The evaluation followed all steps of the flow chart in Figure 10 (IEC 62232:2017).

16.3.2.2 Methodology

The 5G small cells had the following configurations.

- Indoor small cell: The small cell for the demonstration and measurements was using one 2×2 MIMO device resulting in a maximum downlink EIRP of 35 dBm.
- Outdoor small cell: The outdoor configuration consisted of three small cells mounted at a height of 44 m on the tower. This case study measured the RF exposure levels from one of the small cells at a distance of 175 m (outdoor location 1) and 250 m (outdoor location 2) in an area that was publicly accessible and had LoS to the tower. The measurement locations where chosen following desktop calculations to identify areas of predicted maximum exposure. The maximum downlink EIRP for the measured outdoor small cell was 45 dBm.

The small cells were configured to operate at maximum power by using an application layer that filled all resource blocks. The measurement location was well into the far field in source region 3 specified in 7.2.3 (IEC 62232:2017). The measurement of electric field strength was selected, and the value converted to equivalent power density.

A frequency selective instrument and calibrated antenna measuring both vertical and horizontal polarization was used for the assessment. The calibrated antenna mounted on an insulated tripod was rotated through the vertical and horizontal polarizations to measure a peak reading. For the indoor measurements the height of the probe above ground level was 1,5 m. For the outdoor measurements, the height ranged between 1,5 m and 1,8 m.

The spectrum analyser was set to the centre frequency for the 5G small cell and placed into channel power mode and max-hold to ensure that it captured the total power across the 400 MHz channel.

Each measurement was performed over a 1-min to 2-min period to ensure the maximum level was obtained. The maximum level was reached shortly after measurement commenced as the small cell was configured to operate at maximum power for the 2×2 configuration; with all resource blocks utilized for these tests.

16.3.2.3 Reporting

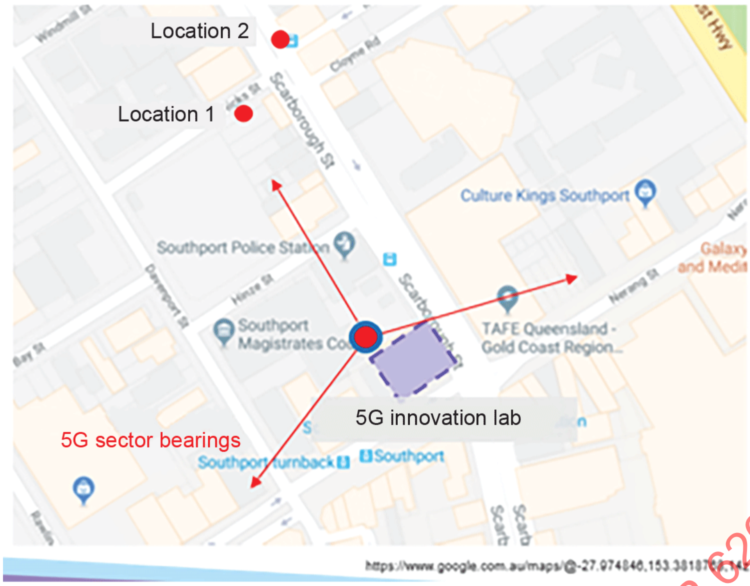
Annex J provides a test report following the requirements of IEC 62232. The measurement uncertainty was determined according to 6.3.3 and Clause 9 (IEC 62232:2017) and a report was prepared according to 6.3.4 and Clause 10 (IEC 62232:2017).

16.3.3 Technical outcome

The measurement results of the power flux density from the 5G small cell are presented in Table 27. The indoor measurements were taken during a gaming mode demonstration whereas the outdoor measurements were taken to replicate maximum downlink traffic. The measurement locations are displayed in Figure 31 to Figure 33.

Table 27 – Measurement results

Measurement locations	**TDD downlink duty cycle**	**Measurement results – peak RMS** (W/m^2)	**Exposure ratio (percentage of ICNIRP limits [8])**
5G laboratory, location 1	50 %	$1,2 \times 10^{-3}$	0,01 %
5G laboratory, location 2	50 %	$2,7 \times 10^{-4}$	0,003 %
5G laboratory, location 3	50 %	$5,5 \times 10^{-4}$	0,006 %
5G laboratory, location 4	50 %	$2,2 \times 10^{-4}$	0,002 %
Outdoor location 1	96 %	$2,0 \times 10^{-4}$	0,002 %
Outdoor location 2	96 %	$9,6 \times 10^{-5}$	0,001 %



IEC

Figure 31 – Map of the outdoor measurement locations

IEC

Figure 32 – Outdoor measurement location 1

IEC

Figure 33 – Outdoor measurement location 2

16.3.4 Lessons learned

On occasions the maximum field strength levels were found to correspond to reflections from objects in the vicinity of the BS antenna rather than the direct beam from the BS antenna. In general, however, the maximum exposure was found to correspond to a single angle of incidence. Thus, to capture the maximum exposure it was essential to sweep and rotate the probe in all possible directions to get an accurate measurement reading.

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

a) add a more sophisticated measurement procedure and post-processing scheme for using directional probes and for other site locations with strong multipath wave propagation;

b) add a method to generate the downlink signal if there is no active traffic in the mobile network, for example using a dedicated device;

c) add an extrapolation method to assess the maximum possible exposure, for example using a decoded reference signal or specific BS configurations, e.g. to maximize the TDD downlink duty cycle.

17 Wireless link with parabolic dish antenna product compliance assessment

17.1 General description

This case study describes a product compliance assessment of mobile back-haul and radio relay products employing a parabolic dish antenna using 6.1 (IEC 62232:2017) and calculation based methods specified in Clause F.11 (IEC 62232:2017), taking into account the amendment described in Annex K and ETSI TR 102 457 [41].

Dish antennas are generally used at frequencies above 2 GHz. They are composed of a main reflector of parabolic shape with symmetry of revolution. The diameter of the main reflector is large compared to the wavelength, which provides a high directivity of the main beam and very little RF-EMF outside the main beam. Therefore, the far-field distance can be far away from the antenna.

Dish antennas are typically used for point-to-point transmission. In general, they are installed in such a way that the general public cannot obstruct the beam.

Many parabolic dish antennas used in mobile back-haul systems use low transmitted power and therefore ensure touch compliance conditions for the general public. However, when used in long haul radio relays or earth stations for satellite systems, significant exposure compliance distances can be achieved for the general public and for workers alike.

Examples of radio transmitters using parabolic dish antennas are shown Figure 34.

a) Mobile back-haul (0,3 m diameter)   b) Radio relays (1,2 m diameter)

Figure 34 – Typical radio transmitters using parabolic dish antennas

The purpose of the assessment is to determine a RF compliance boundary outside of which the RF exposure is below the ICNIRP general public and occupational exposure limits provided in Table 28 (from [8]).

Table 28 – RF EMF exposure limits relevant for the product compliance assessment (from [8])

Frequency band (GHz)	**RF EMF exposure limit** (W/m^2)	
	General public	**Occupational**
2 to 100	10	50

The spatial averaging area (Ae) used in the assessment is 20 cm^2 as specified in [8].

17.2 Implementation of IEC 62232:2017

17.2.1 Evaluation process

The compliance boundary takes the shape of a cylinder with a diameter corresponding to the diameter of the antenna (see Figure 35). The main objective of the RF compliance boundary evaluation is to evaluate the compliance distance in front, CD_{los}, corresponding the height of the cylinder.

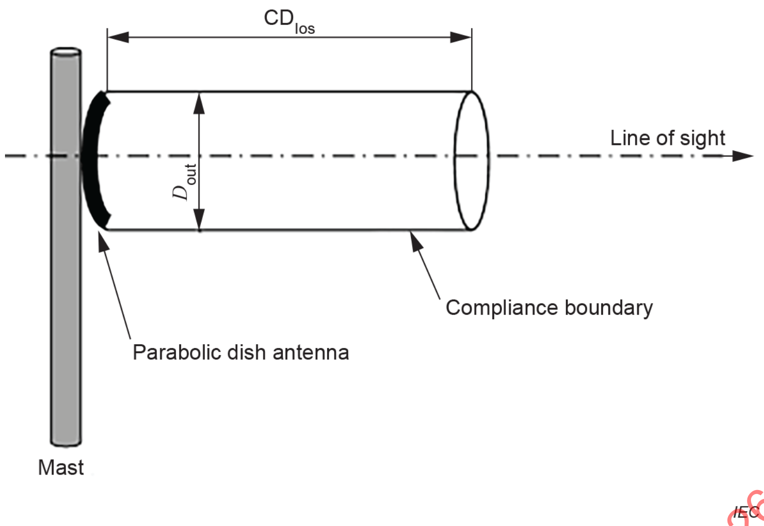


Figure 35 – Cylindrical shape RF compliance boundary

Implementing measurement techniques requires a complex set-up (anechoic chamber, probe positioner, etc.). The general approach is to implement a simplified calculation method that has been derived from either measurement or advanced computation techniques. The full rationale of the calculation method is presented in ETSI TR 102 457 [41]. The flow chart shown in Figure K.1 has been used for this case study as explained in Annex K. The tested equipment has a transmitting frequency in the 7 GHz to 26,5 GHz range and the antenna diameters range from 0,3 m to 1,2 m.

17.2.2 Methodology

A limited number of parameters are required for the implementation of the flow chart. These are mainly:

- transmitting frequency;
- transmitted power;
- gain;
- diameter of the parabolic dish.

In the evaluation of 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 is considered as reasonably foreseeable.

The flow chart and calculation formulas also take into account additional criteria such as:

- whether the diameter is evaluated internally (i.e. exact dimensions of the metallic dish used for manufacturing) or externally (i.e. measured on a finished product);
- far-field compliance distance.

17.2.3 Reporting

The modelling uncertainty is determined according to 6.1.6 and Clause 9 (IEC 62232:2017). The results are reported according to 6.1.7 and Clause 10 (IEC 62232:2017).

17.3 Technical outcome

For the benefit of this document, four examples have been used in order to follow various routes of the flow chart. The main parameters and calculation results are provided in Table 29 and Table 30.

Table 29 – Examples of radio relay configurations with parabolic dish antennas below 10 GHz

Parameter	Touch compliant configuration	Configuration using R_{ff}	Configuration using the far-field formula
Frequency (GHz)	7	8,5	8,5
Inner diameter (m)	1,2	1,2	0,9
Gain (dBi)	35	38	36
Transmitted power (dBm)	26	33	33
Transmitted power (W)	0,4	2	2
S_{lim} GP (W/m^2)	10	10	10
S_{lim} W (W/m^2)	50	50	50
S_{max} (W/m^2)	2,9	14,4	25,6
R_{ff} (m)	67	82	46
CD_{los} (m) for general public	0	5,1	8
CD_{los} (m) for workers	0	0	0

Table 30 – Examples of radio relay configurations with parabolic dish antennas above 10 GHz

Parameter	Touch compliant configuration	Configuration using R_{ff}	Configuration using the far-field formula
Frequency (GHz)	26,5	15,4	19,7
Inner diameter (m)	0,3	0,6	0,3
Gain (dBi)	36,5	37	34
Transmitted power (dBm)	18	26	23
Transmitted power (W)	0,063	0,4	0,2
S_{lim} GP (W/m^2)	10	10	10
S_{lim} W (W/m^2)	50	50	50
S_{max} (W/m^2)	7,3	11,5	23,1
R_{ff} (m)	16	37	12
CD_{los} (m) for general public	0	2,3	2,0
CD_{los} (m) for workers	0	0	0

Outside of this cylinder the RF exposure is below the exposure limits specified by ICNIRP [8], see Table 28.

17.4 Lessons learned

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

a) include the simplified evaluation process and flow chart for BS using parabolic dish antennas in the normative part of the standard, for example in Annex B (IEC 62232:2017) using the amendment described in Annex K;

b) add modelling uncertainty evaluation;

c) add any necessary update due to the definition of RF exposure limits at millimetre wave frequencies.

Since the development of IEC 62232:2017, new point-to-point systems have been specified to address 5G requirements, see for example [42] and [43]. The operating frequency for these systems is between 100 GHz and 200 GHz. Extension of the upper boundary of the frequency range of RF exposure assessment techniques should be considered for the next edition of IEC 62232.

Annex A
(informative)

Technical information supporting the case study "Indoor small cell product compliance assessment using SAR measurements" (Clause 6)

A.1 Technical details

The technical data for the indoor small cell (the EUT) are summarized in Table A.1. The rated maximum transmitted power levels from the EUT and the maximum transmitted power including a 2 dB power tolerance are given in Table A.2. The power tolerance is provided by the client and relates to the manufacturing dispersion and operational environmental conditions (temperature).

Table A.1 – Technical data for the EUT

Product specifications	**Local area BS product**		
Supported bands, Tx frequency range (MHz), and standards	Band 1 Band 7	2 110 MHz to 2 170 MHz 2 500 MHz to 2 700 MHz	WCDMA/LTE LTE
Dimensions, height × depth (mm)	51 × 139		
Antennas	Two internal antennas per radio		

Table A.2 – EUT configuration with rated maximum transmitted power level and maximum transmitted power levels

Band	**Standard**	**Rated maximum transmitted power from the EUT** (dBm/mW)	**Maximum transmitted power** (dBm/mW)
B1 (2 100 MHz) and B7(2 600 MHz)	WCDMA/LTE	23 / 200	25 / 316

A.2 Test report

The test report can be downloaded from the IEC TC 106 dashboard using the following link: https://www.iec.ch/dyn/www/f?p=103:227:4827668868952::::FSP_ORG_ID,FSP_LANG_ID:1303,25

NOTE Measurement equipment or computation software references used in the test report(s) are trade names of commercially available products used during tests. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

Annex B
(informative)

Technical information supporting the case study "Outdoor small cell product compliance assessment using SAR measurements" (Clause 7)

B.1 Physical parameters of the EUT antenna

The physical parameters of the antenna under test are listed in Table B.1. Figure B.1 shows the appearance of the antenna.

Table B.1 – Physical parameters

Antenna type	Plane antenna
Supported frequencies	3,5 GHz band
Number of branches	2
Horizontal directivity	Unidirectional
Configuration of elements	Combination of cross-dipoles
Diversity	H- and V-polarization
Size (mm)	Under 150 × 150 × 60

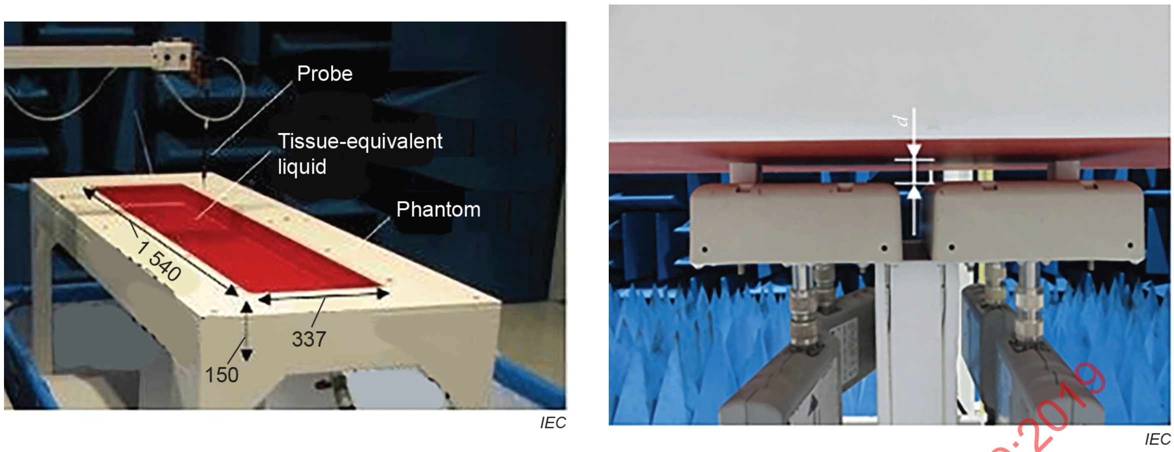
B.2 Measurement set-up

Antennas were located underneath the flat phantom. The separation distance was the distance between the outside surface of flat phantom and the surface of the radome of the antenna. Figure B.1 shows a view of EUT positioning during the SAR measurements and the separation distance (d).

The transmitted power of 0,96 W per port was supplied to the EUT using conventional vector signal generators and amplifiers. The transmitted power was monitored by power reflection meters and directional power sensors. Uncorrelated MIMO signals were provided by vector signal generators above.

Post-processing procedure to derive localized 10 g SAR and whole-body SAR from SAR distribution is derived from IEC 62232:2017 and also described in [13].

Dimensions in millimetres



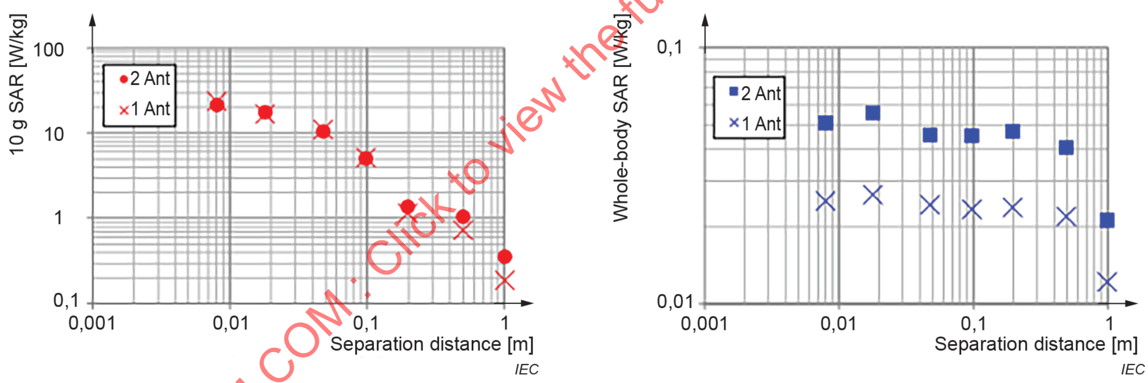
a) Phantom

b) EUT antenna positioning on the phantom

Figure B.1 – Views of the SAR measurement setup

B.3 Measurement results

Figure B.2 a) and b) show the characteristics of 10 g SAR and whole-body SAR as a function of separation distance, respectively. One or two antennas were used for SAR measurements.



a) 10 g SAR

b) Whole-body SAR

Figure B.2 – Characteristics of SAR of EUT antennas as a function of separation distance at 3,5 GHz

B.4 Test report

The test report can be downloaded from the IEC TC 106 dashboard using the following link: https://www.iec.ch/dyn/www/f?p=103:227:4827668868952::::FSP_ORG_ID,FSP_LANG_ID:1303,25

NOTE Measurement equipment or computation software references used in the test report(s) are trade names of commercially available products used during tests. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

Annex C
(informative)

Technical information supporting the case study "Small cell product installation compliance assessment using simplified installation criteria" (Clause 8)

C.1 3GPP categories of base stations

The 3GPP is the international standardization body in charge of specifying telecommunications systems such as 2G, 3G and 4G. The 3GGP has specified four power classes: Wide area BS, Medium range BS, Local area BS and Home BS based on transmitted power levels specified in 3GPP TS 25.104 [16] and 3GPP TS 36.104 [17] and listed in Table C.1.

Table C.1 – Range of transmitted power classes for 3G and 4G base stations (from 3GPP TS 25.104 [16] and 3GPP TS 36.104 [17])

3GPP BS class	Rated maximum transmitted power per carrier per connector
Wide area BS	[a]
Medium range BS	< +38 dBm (6,3 W)
Local area BS	< +24 dBm (250 mW)
Home BS	< +20 dBm (100 mW, for one transmit antenna port) < +17 dBm (50 mW, for two transmit antenna ports) < +14 dBm (25 mW for four transmit antenna ports) < +11 dBm (12,5 mW for eight transmit antenna ports)

[a] There is no upper limit for the rated maximum transmitted power per port of the wide area BS.

C.2 E0 installation class case study – Touch compliant

E0 installation class corresponds to product complying with IEC 62479 or having zero RF compliance boundary dimensions using the assessment methods specified in IEC 62232:2017. A typical E0 scenario might consist of a network operator offering a home BS (also called a femto cell) to its customers; the equipment being installed by the end user. The entity responsible for placing the small cell on the market (e.g. small cell vendor) provides the information included in Table C.2 in the technical documentation of the product.

Table C.2 – Example of product parameters for an E0 installation class

Base station	**Frequency band**	B1 (2 110 MHz to 2 170 MHz)	B7 (2 620 MHz to 2 690 MHz)
	Rated maximum transmitted power	20 mW	20 mW
Typical antenna	**Gain**	2 dBi	2 dBi
Typical site	**EIRP max.**	64 mW	
Typical RF compliance boundary	The product complies with RF exposure limits at zero distance.		
Manufacturer's installation guidelines	None for RF compliance. Other installation guidelines can still be provided for different aspects, e.g. electrical safety, water exposure.		

The network operator provides an installation guide together with the equipment. The installation guide includes general product safety guidelines. An example of installation is provided in Figure C.1.

IEC

[SOURCE: Small Cell Forum]

Figure C.1 – Example of an E0 installation class configuration

C.3 E2 installation class case study

A typical E2 scenario might consist of a network operator (or any entity responsible for putting into service) intending to deploy a multiband LTE local area base station inside premises. The entity responsible for placing the small cell on the market (e.g. small cell vendor) has provided the information included in Table C.3 in the technical documentation of the product.

Table C.3 – Example of product parameters for an E2 installation class

Base station	**Frequency bands (DL)**	B1 (2 110 MHz to 2 170 MHz)	B7 (2 620 MHz to 2 690 MHz)
	Rated maximum transmitted power	250 mW	2 × 250 mW
Typical antenna	**Gain**	3 dBi	3 dBi
	Horizontal beam width	Not applicable	Not applicable
	Vertical beam width	Not applicable	Not applicable
Typical site	**EIRP total max.**	1,5 W	
Typical RF compliance boundary	**Distance in the main lobe**	1 cm (general public) 0 cm (occupational)	
	Distance in other directions	0 cm (general public and occupational)	
Manufacturer's installation guidelines	"The product must be installed in such a way that the general public cannot directly access within a distance of 1 cm in the main lobe of the antenna."		

The entity responsible for putting the equipment into service can deploy the equipment without detailed RF evaluations provided that the installation is performed in such a way that the general public cannot directly access within 1 cm of the equipment antenna as recommended in the manufacturer's installation guidelines. An example of such installation is provided in Figure C.2.

IEC

[SOURCE: Small Cell Forum]

Figure C.2 – Example of an E2 installation class configuration

Upon request by the authorizing body, the entity responsible for putting the equipment into service provides a technical file including the relevant information about this product (derived from Table C.3).

C.4 E10 installation class case study

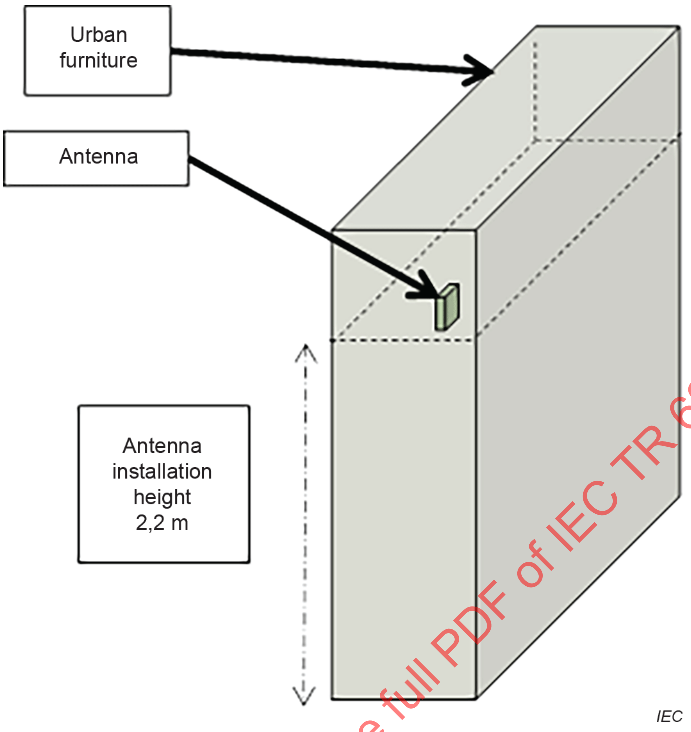
A typical E10 scenario might consist of a network operator (or any entity responsible for putting into service) intending to deploy a group of a multiband LTE local area BS integrated in street furniture advertisement panels across a large urban area.

The entity responsible for placing the small cell on the market (e.g. small cell vendor) provides the information included in Table C.4 in the technical documentation of the product.

Table C.4 – Example of product parameters for an E10 installation class

Base station	**Frequency bands (DL)**	B3 (1 805 MHz to 1 880 MHz)	B7 (2 620 MHz to 2 690 MHz)
	Rated maximum transmitted power	2 × 250 mW	2 × 250 mW
Typical antenna	**Gain**	8 dBi	9 dBi
	Horizontal beam width	70°	50°
	Vertical beam width	70°	60°
Typical site	**EIRP total max.**	7,1 W	
Typical RF compliance boundary	**Distance in the main lobe**	5 cm (general public) 0 cm (occupational)	
	Distance in other directions	0 cm (general public and occupational)	
Manufacturer's installation guidelines	"The product must be installed in such a way that the general public cannot directly access within a distance of 5 cm in the main lobe of the antenna. When installed with a typical antenna of 8 dBi to 9 dBi, the product has an EIRP of less than 10 W and therefore is eligible to simplified installation class E10 as specified in 6.2.3 (IEC 62232:2017). As such it can be installed at a minimum height of 2,2 m without additional RF exposure assessment."		

The entity responsible for putting the equipment into service ensures that the product is integrated in the street furniture in such a way that the antenna installation height is 2,2 m from ground level as specified in the manufacturer's instructions. The final installation design criteria are displayed in Figure C.3.



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

Figure C.3 – Example of layout design for an E10 installation class configuration

The entity responsible for putting the equipment into service would be able to put all similar equipment into service without field calculations or measurements. Upon request by the authorizing body, this entity would be able to provide a technical file including the relevant information about the product (from Table C.4) and the installation layout design provided in Figure C.3.

C.5 E100 installation class case

A typical E100 scenario might consist of a network operator (or any entity responsible for putting into service) intending to deploy a group of LTE medium range base stations integrated on a mast used for street furniture (e.g. lamp post, traffic light) deployed across a large urban area. The entity responsible for placing the small cell on the market (e.g. small cell vendor) provides the information included in Table C.5.

Table C.5 – Example of product parameters for an E100 installation class

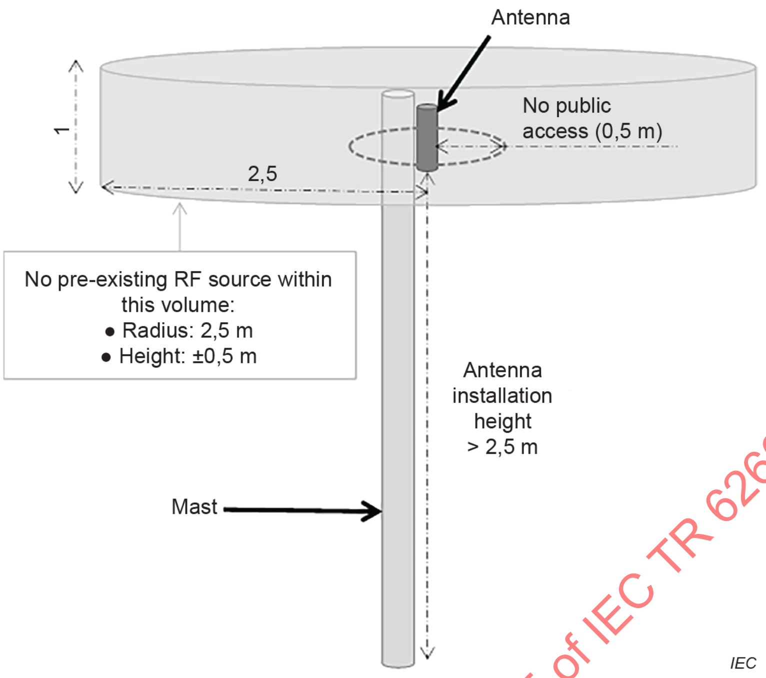
Base station	**Frequency band**	B3 DL (1 805 MHz to 1 880 MHz)
	Rated maximum transmitted power	2 × 5 W
Typical antenna	**Gain**	10 dBi
	Horizontal beam width	70°
	Vertical beam width	70°
Typical site	**EIRP max.**	100 W
Typical RF compliance boundary	**Distance in the main lobe**	50 cm (general public) 15 cm (occupational)
	Distance in other directions	15 cm (general public and occupational)
Manufacturer's installation guidelines	"The product must be installed in such a way that the general public cannot access within a distance of 50 cm in the main lobe of the antenna. When installed with a typical antenna of 10 dBi, the product has an EIRP of 100 W and therefore is eligible to simplified installation class E100 as specified in 6.2.3 (IEC 62232:2017). It is recommended to install this equipment at a minimum height of 2,5 m above the general public walkway. Workers must not stand within 15 cm in front of the antenna unless the transmitted power has been switched off."	

The entity responsible for putting the equipment into service ensures that the product is installed according to manufacturer's instructions and integrated in the street furniture in such a way that:

- the antenna installation height is more than 2,5 m from ground level;
- the general public cannot access the area within 50 cm in the main lobe of the antenna;
- there is no pre-existing transmitter with an EIRP of 10 W or above within 2,5 m from the small cell antenna.

The final installation design criteria for RF compliance are displayed in Figure C.4. The operator also ensures that the installation complies with all other requirements related to the technology used as specified by the 3GPP.

Dimensions in metres



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

Figure C.4 – Example of layout design for an E100 installation class configuration

The entity responsible for putting the equipment into service would be able to put all subsequent similar equipment into service without field calculations or measurements. Upon request, this entity would be able to provide a technical file including the relevant information about the product (from Table C.5) and the installation layout design provided in Figure C.4.

C.6 E+ installation class case study

A typical E+ scenario is consisting of a network operator (or any entity responsible for putting into service) that is intending to deploy a group of LTE medium range BS integrated on a mast used for street furniture (e.g. lamp post, traffic light) in a large urban area. The entity responsible for placing the small cell on the market (e.g. small cell vendor) provides the information included in Table C.6, based on IEC 62232:2017 requirements.

Table C.6 – Example of product parameters for an E+ installation class

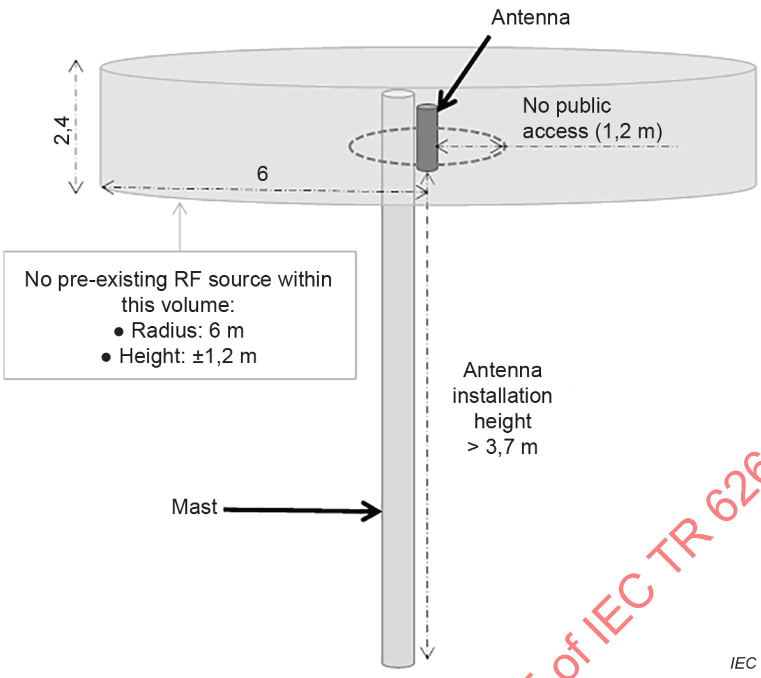
Base station	**Frequency bands (DL)**	B1 (2 110 MHz to 2 170 MHz)	B7 (2 620 MHz to 2 690 MHz)
	Maximum transmitted power	5 W	2 × 5 W
Typical antenna	**Gain**	13 dBi	13 dBi
	Horizontal beam width	60°	60°
	Vertical beam width	25°	25°
	Side lobe suppression	13 dB	13 dB
Typical site	**EIRP total max.**	300 W	
	Down tilt	4°	
Typical RF compliance boundary	**Distance in the main lobe**	1,2 m (general public) 0,5 m (occupational)	
	Distance in other directions	15 cm (general public and occupational)	
Manufacturer's installation guidelines	"The product must be installed in such a way that the general public cannot access within a distance of 1,2 m in the main lobe of the antenna. When installed with a typical antenna of 13 dBi, the product has an EIRP of 300 W and therefore is eligible to simplified installation class E+ as specified in 6.2.3 (IEC 62232:2017). It is recommended to install this equipment at a minimum height H_m of 3,7 m above the general public walkway and with no pre-existing RF source with EIRP above 100 W installed within a distance of 6 m in the main lobe direction and within 1,2 m in other directions. Workers must not stand within 50 cm in front of the antenna unless the transmitted power has been switched off."		

The entity responsible for putting the equipment into service ensures that the product is installed according to manufacturer's instructions and integrated in the street furniture in such a way that:

- the antenna installation height is more than 3,7 m from ground level;
- the general public cannot access the area within 1,2 m in the main lobe of the antenna;
- there is no pre-existing transmitter with an EIRP of 100 W or above within 6 m from the small cell antenna.

The final installation design criteria for RF compliance are displayed in Figure C.5. The operator also ensures that the installation complies with all other requirements related to the technology used as specified by the 3GPP.

Dimensions in metres



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

Figure C.5 – Example of layout design for an E+ installation class configuration

The entity responsible for putting the equipment into service would be able to put all subsequent similar equipment into service without field calculations or measurements. Upon request, this entity would be able to provide a technical file including the relevant information about the product (from Table C.6) and the installation layout design provided in Figure C.5.

Annex D
(informative)

Technical information supporting the case study "Small cell site in-situ measurements" (Clause 9)

D.1 General description and note

Annex D provides additional technical details about small cell in-situ measurement Campaigns A (see 9.2) and B (see 9.3) performed by two independent entities.

NOTE Equipment references used in Annex D are trade names of commercially available products used during tests. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

D.2 Technical information and results for measurement Campaign A

The measurement campaign has been performed on two different trials in different urban areas in French cities. Trial 1 was in a city with about 2 000 inhabitants per km^2 and Trial 2 was in a much denser city with about 12 000 inhabitants per km^2. Obviously, these two trials are not comparable in terms of data traffic demand. The main characteristics of equipment used for these two trials are summarized in Table D.1.

Table D.1 – Main characteristics of the two trials of measurement Campaign A

Characteristic	Trial 1	Trial 2
City	Annecy, France	Montreuil, France
Number of sites	4	5
Frequency bands	B7 (2 620 MHz to 2 690 MHz)	B7 (2 620 MHz to 2 690 MHz) B3 (1 805 MHz to 1 880 MHz)
Type of antennas	Directive	Directive
Height of antennas	3 m	3 m or 5 m
Number of intermediate measurements	129	151

The measurement area is within a 100 m radius around each site to assess the exposure in the assumed coverage area of the small cells. This measurement area is separated in two sub-areas: a very close one within 20 m of the small cell and the remaining area within 100 m. The measurements are performed twice, first with small cells on and then with small cells off to be able to make a comparison.

The very close sub-area is characterized by a scan over the measurement area at a height of 1,5 m above the ground in order to find the location of the maximum exposure. The further sub-area is characterized by scanning the area with pre-determined measurement points at a height of 1,5 m to cover all accessible areas in the 100 m radius zone. Each of the intermediate measurements are reported. The detailed assessment (Case B) is performed at the location of the maximum exposure when small cells are ON. When small cells are OFF, measurements are performed at the same location (intermediate and detailed measurements).

At a large scale (i.e. within the 100 m radius zone around each site), the impact of small cells on the mean value of E-field measurements with broadband equipment during site analysis is limited, as shown by Figure D.1.

When the small cells are in service, the average E-field in the 100 m radius area was between 0,17 V/m and 0,55 V/m and between 0,15 V/m and 0,54 V/m when small cells are OFF.

All of the exposure levels assessed before and after putting the small cells into service were well below the French regulatory exposure limits (see [8]).

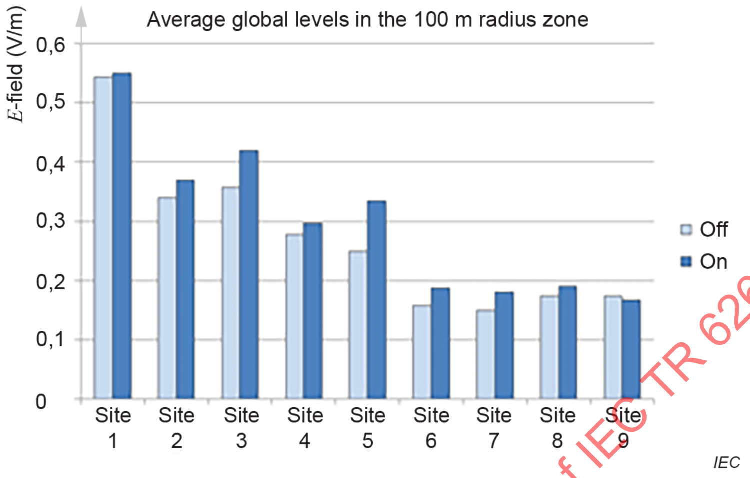


Figure D.1 – Mean value of E-field measurements with broadband equipment at intermediate points for each site

Very localized and close to the site, maximum values between 1 V/m and 3 V/m have been measured, as shown in Figure D.2. These maximum levels of exposure induced in close proximity to small cells are comparable with levels of exposure that can be induced by existing macro antennas. Indeed, in France in 2016, 1 % of measured levels in urban areas were above 5,6 V/m, from [44].

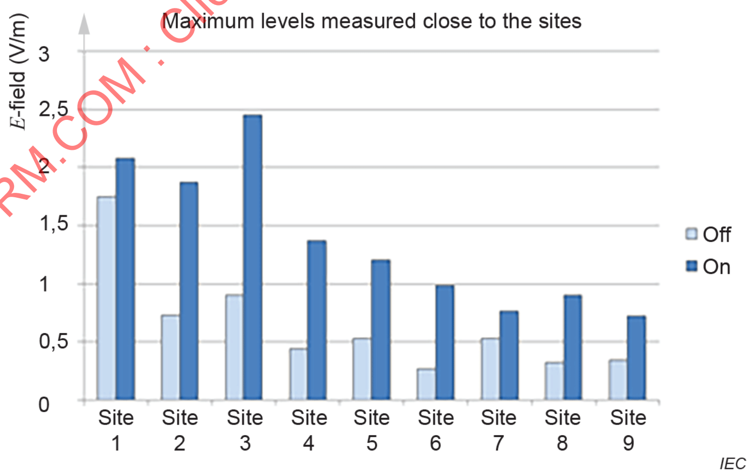


Figure D.2 – Maximum global E-field values measured in close proximity to the sites

As the results are above or around 1 V/m when small cells are in service, a consistency analysis between Case A results and Case B results without extrapolation has been performed as explained in 9.2.2.4. As shown on Figure D.3, the consistency is acceptable (less than 20 % of differences between both results) and Case A results were higher than Case B results.

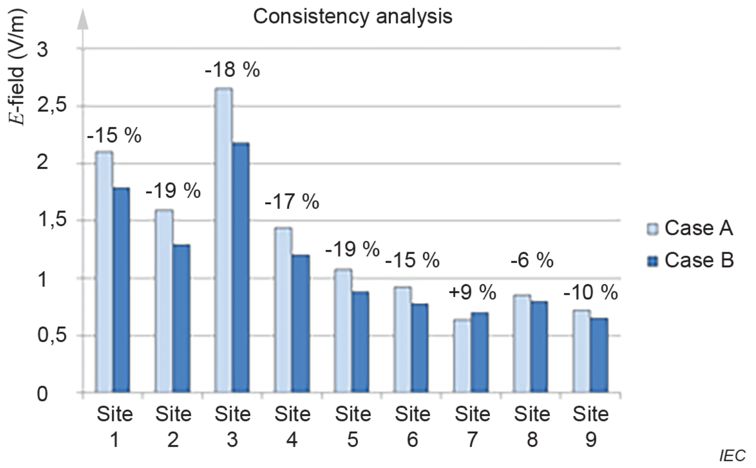


Figure D.3 – Consistency analysis between Case A and Case B (without extrapolation) results

At the location of maximum exposure, Case B measurements have been performed to have a detailed analysis of the exposure. As illustrated in Figure D.4, the strongest contributions in the exposure levels are mobile services.

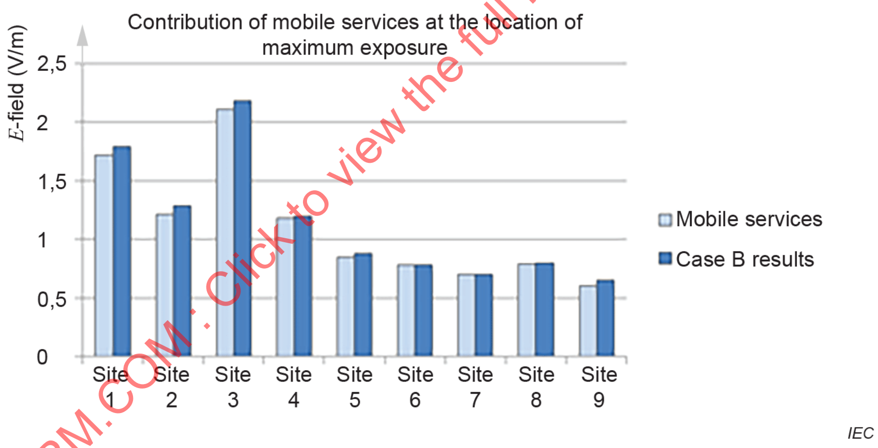
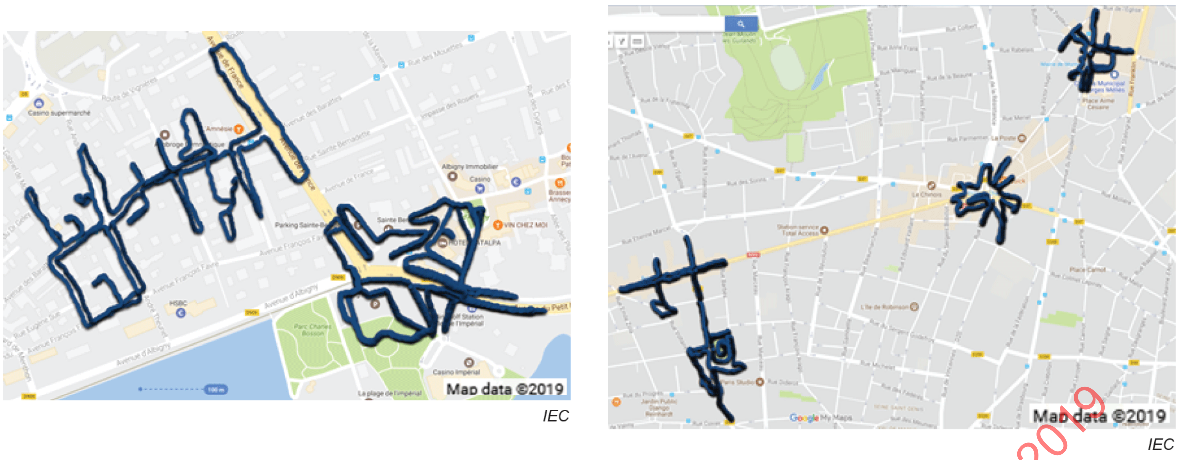


Figure D.4 – Contribution of mobile services compared to Case B results

Complementary field tests have been performed using handheld drive test device to evaluate the impact of the small cell from the device point of view. This information was used for providing general information about the benefits of installing small cells. Connection to small cells is expected to reduce the power transmitted by the device and to increase the throughput available. Walk tests were performed in accessible outdoor areas in 100 m radius zones around each site (see Figure D.5). The handheld drive test device was set up to successively upload 100 MB files on an FTP server and make 30 s voice calls when VoLTE was available.



a) Trial 1 b) Trial 2

Figure D.5 – Routes used for walk-tests around each site on both trials

Figure D.6 compares for the first trial the cumulative distribution function of upload normalized throughput on the left and of the power transmitted by the handset on the right when small cells are switched on (blue lines) and when small cells are switched off (red lines). The upload throughputs have been measured when the handset is uploading successive 100 MB files on an FTP server. Values have been normalized to the maximum values measured when small cells were off for each trial.

It is worth pointing out that, for half of the sites of Trial 1, the macro 4G coverage was excellent and the density of users was limited. Consequently, the upload throughputs obtained when small cells were off were already high. So, in this case, the small cells enable only a small gain on upload throughput (+20 % on median value and no gain on maximum available throughput) as is illustrated on Figure D.6. However, in this case, the small cells enable to reduce significantly the power transmitted by the handset during FTP uploads: the median transmitted power was a factor of four times lower than the macro cell.

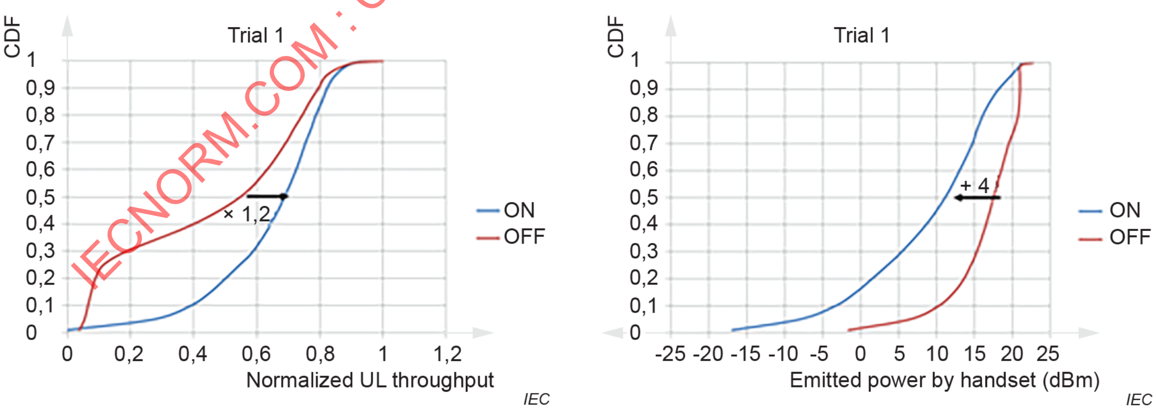
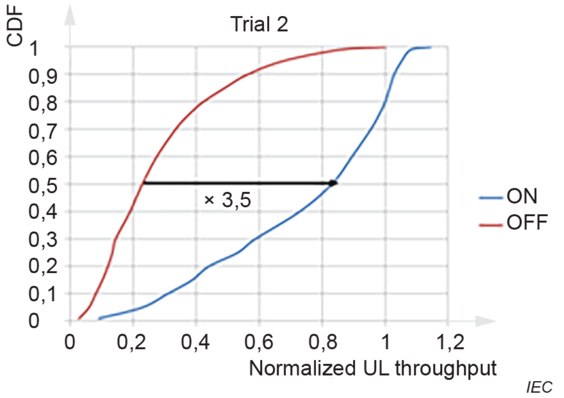


Figure D.6 – Cumulative distribution function of the upload throughput on Trial 1 normalized by the maximum value measured on each site when the small cells are off (left) and of the transmitted power by the handset (right)

On Trial 2, the density of users was high and the small cells enable an important gain on upload throughput (3,5 times on median upload throughput and +20 % on maximal available throughput) as illustrated on Figure D.7. However, the gain on the power transmitted by the handset during the FTP uploads is limited (same median value as illustrated on the right of Figure D.7).



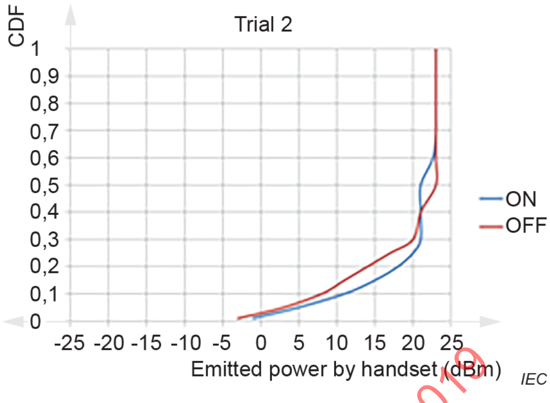


Figure D.7 – Cumulative distribution function of the upload throughput on Trial 2 normalized by the maximum value measured on each site when the small cells are off (left) and of the transmitted power by the handset (right)

In terms of human exposure, both trials produced positive results, albeit for different reasons. In one case, the exposure was reduced in proportion to the difference in transmit powers (between the macro and the small cell), both delivering comparable throughput rates. The other case yielded a higher throughput rate but shorter duration of time-averaged exposure. Therefore, the time-averaged exposure is reduced.

Measurements on VoLTE have also been carried out where the service was available (on Trial 2). The gain on the power transmitted by the handset during voice calls was very high: the median transmitted power during voice calls is 12 times lower when the handset was connected to the small cells instead of macro cells (see Figure D.8).

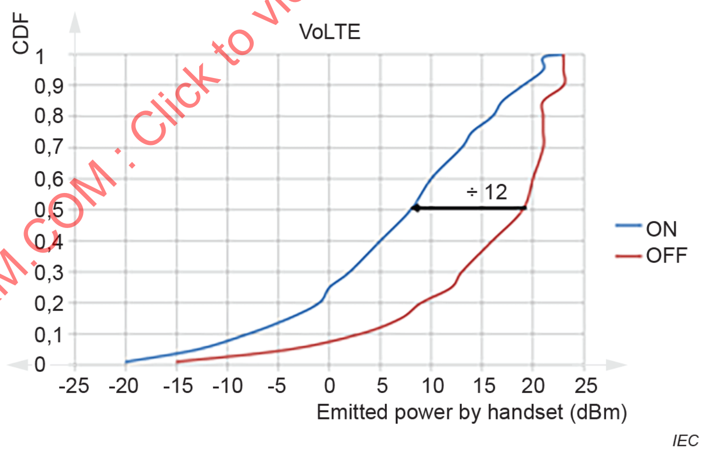


Figure D.8 – Cumulative distribution functions of the power transmitted by the handset during voice calls on Trial 2 when small cells are on and off

An example of test report from measurement Campaign A can be downloaded from the IEC TC 106 dashboard using the following link: https://www.iec.ch/dyn/www/f?p=103:227:4827668868952::::FSP_ORG_ID,FSP_LANG_ID:1303,25

The report is related to one site of Trial 2.

NOTE Measurement equipment or computation software references used in the test report(s) are trade names of commercially available products used during tests. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

D.3 Technical information for measurement Campaign B

D.3.1 General description

Measurement Campaign B consisted of performing in-situ measurements of the RF exposure around small cell installations. It was performed on 98 sites located in South Africa (80), the Netherlands (16) and Italy (2).

Sites were selected from available network operator information. In South Africa, only sites in three metro areas were considered. For this study, only sites with a power per frequency band at the antenna port of less than 6 W were considered (see Table C.1) consistent with the 3GPP power classes, see [16] and [17].

Sites were classified into three groups: "Indoor", "Outdoor 2 m to 4 m" and "Outdoor > 4 m", as detailed in 9.3.1. Table D.2 shows the classification and country of the 98 sites contained in measurement Campaign B.

Table D.2 – Country and site groups of the sites in measurement Campaign B

Country	Indoor	Outdoor 2 m to 4 m	Outdoor > 4 m	Total
South Africa	47	12	21	80
Netherlands	-	16	-	16
Italy	-	2	-	2
Total	47	30	21	98

D.3.2 Measurement process

As the objective was to provide a detailed evaluation of RF exposure levels, a Case B evaluation was performed. For this specific study, the measured results at the time of the survey were reported. No extrapolation to maximum exposure as specified in B.5.3 (IEC 62232:2017) was performed. An active download from the site being surveyed was maintained for the duration of the measurements. This ensured that the small cell being surveyed was live and carrying traffic at the time of the survey. This downloading device was kept some distance from the frequency selective measurement device to minimize the influence on the measured uplink signals. Measurements were performed between 08h00 and 17h00.

At each installation three positions accessible to the general public are identified and measurements performed at these locations. The first position is chosen as the position of expected maximum exposure close to the site, but not closer than 1 m from the antenna. A further two positions are measured within 50 m of the small cell site. Where relevant, these two additional positions are points of specific interest where people can spend some time or an area frequented by people. Three-point spatial averaged measurements at 1,1 m, 1,5 m and 1,7 m above ground were performed, in accordance with Figure B.10 (IEC 62232:2017). During the measurements, the spectrum analyser and antenna was mounted on a wooden tripod. At each height a measurement is taken over a 60-s period. Thus, for the three heights used, the total measurement time is 180 s. The time-averaged result over the three heights is reported.

The equipment measurement range was set at each position to a level as low as possible, ensuring maximum sensitivity without saturating the spectrum analyser.

A Narda SRM-3006 (SRM) spectrum analyser with a Narda 3501/03[2] three-axis E-field probe, covering the frequency range 27 MHz to 3 GHz, is used. Predefined frequency bands listed in Table D.3 were configured on the device.

Table D.3 – The predefined services configured in the measurement equipment

Service name	f_{min} [MHz]	f_{max} [MHz]
FM	88	108
800 MHz BS downlink	791	821
800 MHz BS uplink	832	862
900 MHz BS uplink	880	915
900 MHz BS downlink	925	960
1800 MHz BS uplink	1 710	1 785
1800 MHz BS downlink	1 805	1 880
2100 MHz BS uplink	1 920	1 980
2100 MHz BS downlink	2 110	2 170
ISM 2,4 GHz	2 400	2 500
2600 MHz BS uplink	2 500	2 570
2600 MHz BS downlink	2 620	2 690

The "wide spectrum" results were reported, as well as the "mobile downlink". The wide spectrum results were the measured level over the operating frequency range of the device/probe combination, i.e. 27 MHz to 3 GHz. Since the study was interested in the mobile BS downlink contribution of the small cells, the "mobile BS DL" results are also given. These results are only the contributions of the mobile network downlink frequencies, a subset of the frequency bands listed in Table D.3.

D.3.3 Results

Figure D.9 shows the results of the measurements performed for this study. The bottom bars indicate the 5th percentile and the top bars the 95th percentile results. The square represents the median result for each dataset. The first result is the wide spectrum result for all the measured positions of this study. The second is the corresponding results for the mobile downlink frequency bands only. The next three results give the mobile downlink results for the three site groups: Indoor, Outdoor 2 m to 4 m and Outdoor > 4 m. Although the number of sites is quite small, no significant difference was observed between the results for the different site groups.

For comparison to other studies, the results are expressed in terms of electric field strength [V/m].

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2 3501/03 is the trade name of a product supplied by Narda Safety Test Solutions GmbH. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

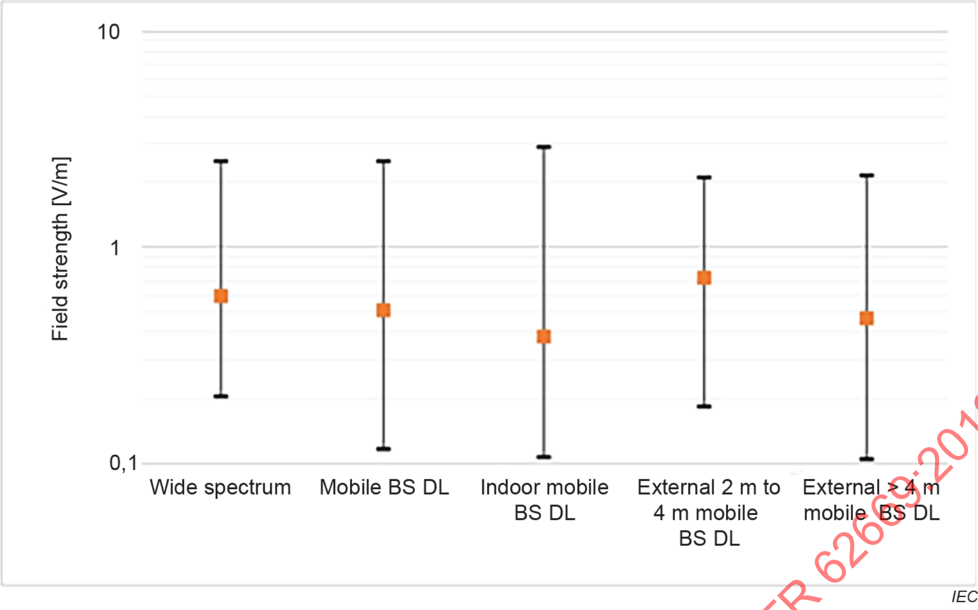

Figure D.9 – Results of the measurements around the selected sites

Figure D.10 uses the same 5th, 95th and median representation as above. The first result is repeated from Figure D.9. The second dataset is that of the small cell study by the ANFR, detailed in Clause D.2. Only measurements of the ANFR campaign where the small cell is on are considered here for comparison. The third dataset is from 9502 measurements performed during 2014 to 2016 as part of the ANFR National French Survey Programme [44]. The fourth result is a general dataset of measurements performed in South Africa around general base stations between 2006 and 2016. This comparison shows very similar exposure levels over the four measurement campaigns.

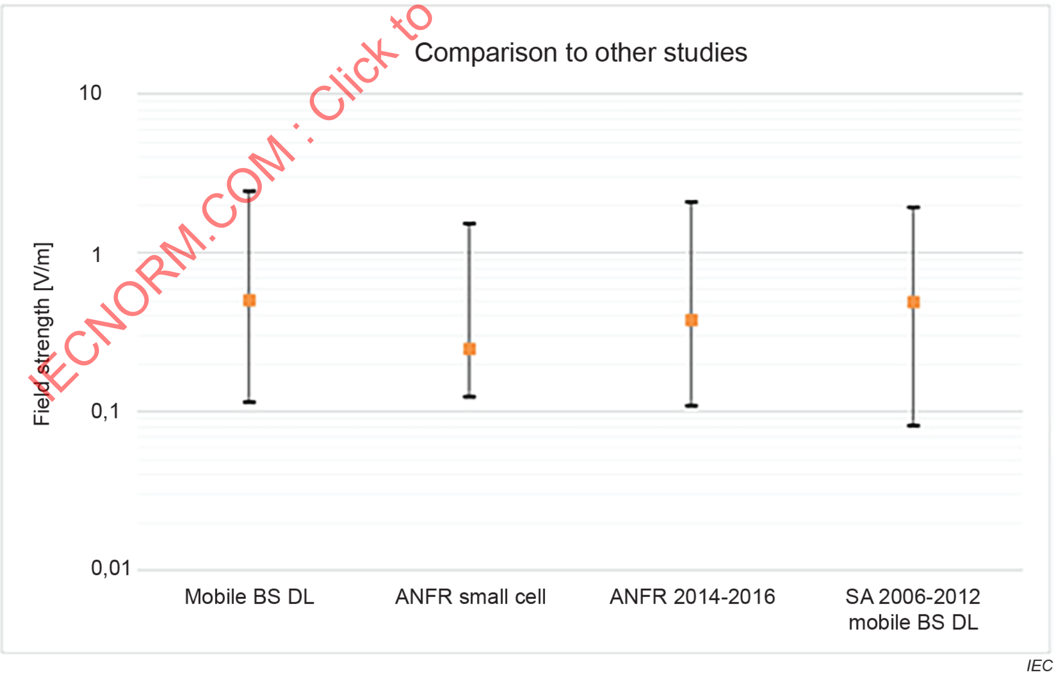

Figure D.10 – Comparison between Campaign B results and other countrywide measurement campaigns