5G veldsterktemetingen in de Effenaar Eindhoven

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Meetrapport

5G veldsterktemetingen in de Effenaar Eindhoven

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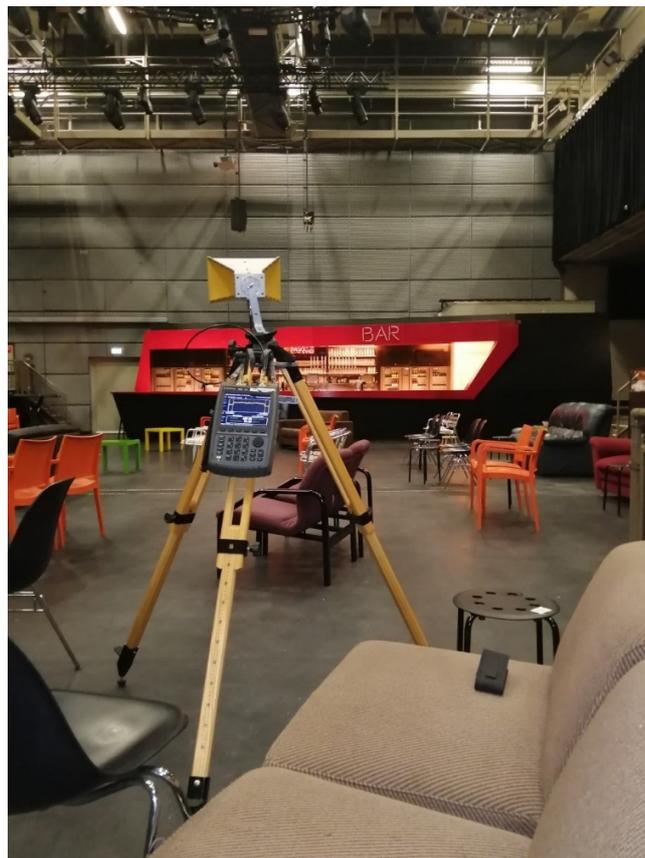
Inhoud

1 Introductie

Vanaf eind januari 2020 worden er op diverse locaties in Eindhoven een serie 5G pilots uitgevoerd door het telecombedrijf VodafoneZiggo en netwerkpartner Ericsson. Één van deze locaties betreft het poppodium de Effenaar. Dit gebouw beschikt over twee zalen; een grote zaal met een capaciteit voor 1300 personen en een kleinere zaal. Voor deze pilot is er een 5G basisstation (BS) antenne geïnstalleerd in de grote zaal. Even zoals BS antennes van voorgaande generaties mobiele systemen (2G, 3G en 4G), produceert deze 5G antenne elektromagnetische velden in de omgeving. Vóór de aanvang van elke pilot worden door de Technische Universiteit Eindhoven de veldsterkteniveaus gemeten op plekken die publiek toegankelijk zijn. Doel van de metingen is vast te stellen hoe deze veldsterkteniveaus zich verhouden tot zowel de wettelijke blootstellingslimieten alsmede de veldsterkteniveaus van de huidige (2G, 3G en 4G) systemen.

2 Metingen in de grote zaal

2.1 Algemene gegevens

Soort meting:	Voorlichtingsmeting
Aanleiding meting:	5G pilots in Eindhoven
Datum meting:	20 augustus 2020
Plaats meting:	Effenaar Eindhoven
Locatie/omgeving:	Indoor meting
Adres meting:	Dommelstraat 2, 5611 CK, Eindhoven

2.2 Gegevens BS antenne

Adres opstelpunt	Dommelstraat 2, 5611 CK, Eindhoven
Opstelpunt	bevestigd 1,5 meter voor zijwand aan mast vanuit plafond
Hoogte opstelpunt	6,5 meter
GPS coördinaten	51,44172 5,481325
Type zendinstallatie	5G New Radio
Gebruikte zender/eNodeB	Ericsson AIR6488
Frequentieband	3,555 – 3,595 GHz (40 MHz bandbreedte)
Antennewinst	12 – 16 dBi (factor 16 – 40 t.o.v. isotrope straler)
Zendvermogen	23 dBm (0,2 W)

2.3 Meetinstrumenten en methode

Gebruikte meetinstrumenten	Keysight FieldFox N9918A RF analyzer (serienr: MY53103773)
	EMCO 3115 hoornantenne (serienr: 6305)
	Meetkabel HP 85100 60002, nr. 267
Type meting	Selectief

Toegepaste meetmethodiek	CENELEC standaard EN 62232, 2017 [1] (zie Appendix B)
	Om ervoor te zorgen dat de BS antennebundel tijdens de meting op de meetopstelling is gericht met maximaal zendvermogen wordt met een 3,5 GHz terminal/User Equipment (UE) in de buurt van de meetantenne een data verbinding opgezet voor een breedbandsnelheidstest. Deze test bewerkstelligt dat er de volledig beschikbare bandbreedte wordt gevraagd en daarmee alle resource blokken van de zender actief zijn.
Gebruikte 3.5 GHz terminal/UE:	Samsung Galaxy S20 5G met Ookla breedbandsnelheidstest
Meetonzekerheid	±33 % (zie Appendix C)

2.4 Beschrijving van de meetlocatie

Figuur 2.1 toont een verticale doorsnede van de meetsituatie in de grote zaal. De gele rechthoek geeft de locatie van de 5G BS antenne, de blauwe ellips toont de richting van de antennebundel en de rode driehoek geeft de locatie van de meetantenne. De groene punt geeft de positie van de UE op enige afstand achter de meetantenne, gezien vanuit de BS antenne. Het polygoon linksonder representeert de bar. Deze bevindt zich onder de BS antenne maar blokkeert niet de zichtlijn.
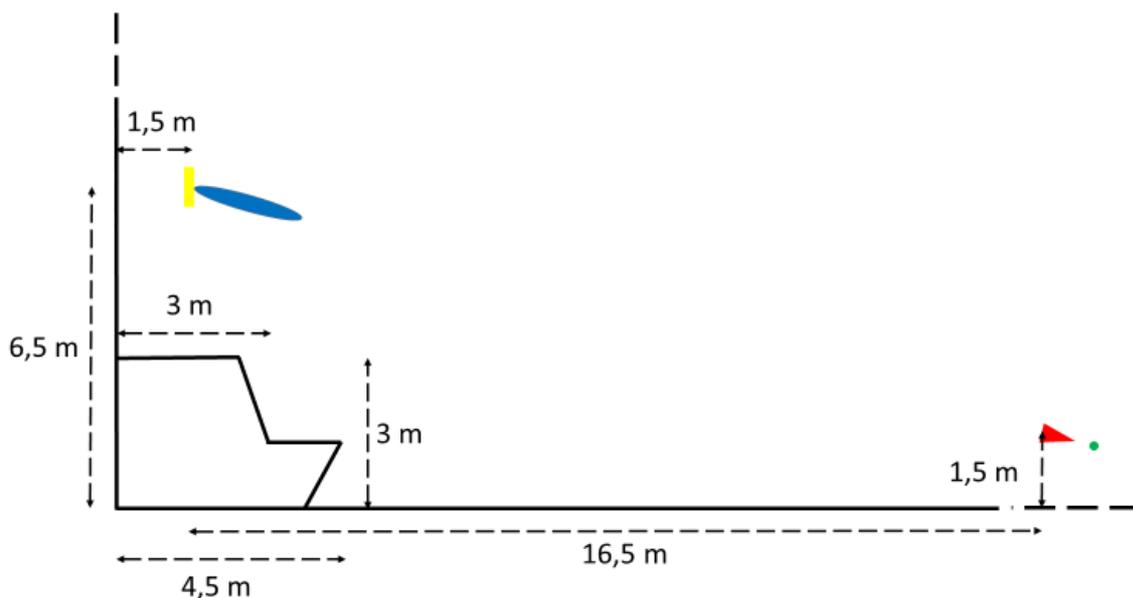
Fig. 2.1 Meetsituatie in de grote zaal

Figuur 2.2 toont de meetopstelling ter plaatse van de meting. De foto is genomen in de richting van de BS antenne die op de achtergrond zichtbaar is als zwarte rechthoek links boven de bar.

Fig. 2.2 Meetopstelling in de grote zaal

2.5 Positie van de meetantenne

GPS coördinaten   51,44170 5,48322
Hoogte   1,5 meter
Horizontale afstand tot BS antenne   16,5 meter

2.6 Meetresultaten

De gemeten maximum veldsterkte in de 5G band binnen de meettijd van 6 minuten bedraagt 0,47 V/m (volt per meter). Dit is de hoogst gemeten waarde in de zaal (en in het hele gebouw). Fig. 2.3 (a) toont de verkregen plot van het frequentiespectrum met de resulterende veldsterkte binnen de toegewezen 5G band die wordt gemarkeerd door de twee verticale lijnen; 113,41 dBµV/m komt overeen met 0,47 V/m. Fig. 2.3 (b) toont de bijbehorende nulmeting zijnde het frequentiespectrum bij uitgeschakeld BS; 88,53 dBµV/m komt overeen met 0,027 V/m, wat overeenkomt met de ruisvloer van het meetinstrument (bij de gegeven instellingen).
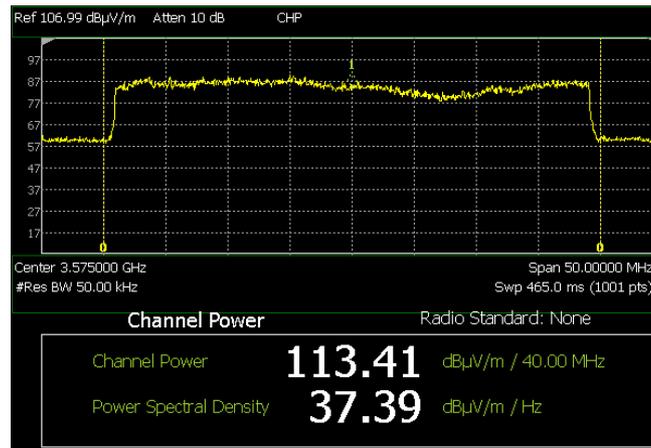
(a)
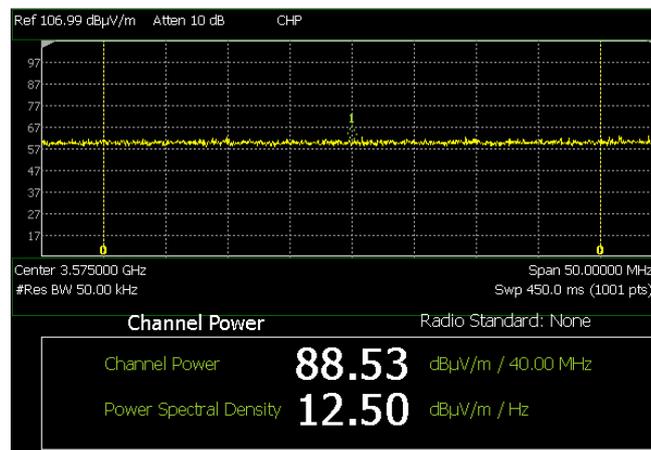
(b)

Fig. 2.3 Frequentiespectrum en veldsterkte bij (a) ingeschakeld BS en bij (b) uitgeschakeld BS.

Er is echter slechts in één polarisatierichting gemeten omdat de meetantenne lineair is gepolariseerd terwijl de BS antenne in twee orthogonale polarisatierichtingen (+45° en -45°) in gelijke mate onderling onafhankelijke signalen uitzendt. De gemeten veldsterkte moet daarom met een factor $\sqrt{2}$ worden gecorrigeerd wat een waarde van 0,66 V/m oplevert.

In het voorgaande is nog geen rekening gehouden met de meetonzekerheid. Daardoor kan de waarde van de werkelijke veldsterkte hoger uitpakken. De meetonzekerheid is 33% (zie Appendix C). Als deze wél wordt meegenomen in de veldsterktebepaling is de veldsterkte aan de bovenkant van het onzekerheidsgebied 33% hoger. Voor de 5G veldsterkte wordt dit dan 0,88 V/m.

Om een indruk te krijgen van de maximale bijdrage van de 5G antenne aan de totale blootstelling geproduceerd door alle 2G/3G/4G en 5G antennes bij elkaar zijn naast het veldsterkteniveau in de gebruikte 5G frequentieband ook de veldsterkteniveaus in de individuele 2G/3G/4G banden gemeten. Alle gemeten waarden, met daarin meegenomen de maximale meetfout, alsmede de blootstellingslimieten zijn vermeld in V/m in Tabel 2.1.

Tabel 2.1 Maximale veldsterkteniveaus en blootstellingslimieten.

Frequentieband	Veldsterkte	blootstellingslimiet
3,5 GHz	0,88 V/m	61,0 V/m
800 MHz	0,04 V/m	38,6 V/m
900 MHz	0,06 V/m	41,8 V/m
1,8 GHz	0,96 V/m	58,3 V/m
2,1 GHz	1,70 V/m	61,0 V/m
2,6 GHz	4,24 V/m	61,0 V/m

Op basis van de bepaalde maximale veldsterkteniveaus kan de maximale bijdrage van de 5G blootstelling aan de totale blootstelling van alle systemen (2G/3G/4G/5G) bij elkaar worden vastgesteld in termen van geabsorbeerd vermogen (opwarming). Hiertoe dient men eerst elke veldsterktewaarde in Tabel 2.1 te delen door de bijbehorende limiet en dit quotiënt te kwadrateren. De som der kwadraten representeert het percentage waarmee de totale blootstelling van alle systemen bij elkaar onder de cumulatieve blootstellingslimiet blijft [2]. De maximale bijdrage van de 5G antenne hieraan voor wat betreft opwarming kan worden bepaald door de kwadraatterm van de 5G bijdrage te delen door deze totaalsom. De aldus bepaalde bijdrage van 5G aan de totale blootstelling bedraagt 3,44%.

2.7 Conclusie m.b.t. de meetresultaten

De veldsterkte geproduceerd door de 5G antenne bedraagt maximaal 0,88 V/m. De bijdrage van de 5G antenne aan de totale blootstelling ten gevolge van alle systemen bij elkaar bedraagt maximaal 3,44%.

3 Samenvatting en eindconclusies

Vanaf eind januari 2020 worden er op diverse locaties in Eindhoven een serie 5G pilots uitgevoerd door het telecombedrijf VodafoneZiggo en netwerkpartner Ericsson. Één van deze locaties betreft het poppodium de Effenaar. Voor deze pilot is er een 5G basisstation (BS) antenne geïnstalleerd in de grote zaal van het gebouw. De Technische Universiteit Eindhoven heeft vóór de aanvang van deze pilot de veldsterkteniveaus gemeten op plekken die publiek toegankelijk zijn. Doel van de metingen is vast te stellen hoe deze zich verhouden tot zowel de wettelijke blootstellinglimieten alsmede de blootstellingsniveaus van de huidige systemen.

Tabel 3.1 geeft een samenvatting van de maximaal geproduceerde veldsterkte alsmede de percentuele bijdrage van de 5G antenne aan het totale blootstellingsniveau veroorzaakt door alle systemen (2G/3G/4G/5G) bij elkaar voor wat betreft het opwarmingseffect. Bij het bepalen van de veldsterktewaarde is uitgegaan van de maximaal mogelijke meetfout zodat deze waarde geldt voor het ongunstigste geval. De resultaten laten zien dat

a) de 5G veldsterkte klein is ten opzichte van de blootstellingslimiet,
b) de 5G bijdrage aan het totale blootstellingsniveau van alle systemen bij elkaar (2G/3G/4G/5G) voor wat betreft opwarming klein is.

Tabel 3.1 Samenvatting van de meetresultaten

Meetlocatie	Veldsterkte 5G antenne	Wettelijke blootstellingslimiet	Bijdrage 5G aan totale blootstellingsniveau
Grote zaal Effenaar	0,9 V/m	61 V/m	3,5%

Referenties

[1] CENELEC standard EN 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, 2017.

[2] International Commission on Non-Ionizing Radiation Protection: Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields. Health Physics 74:494-522, 1998.

Appendix A   Meetresultaten

In de grote zaal van de Effenaar zijn per frequentieband steeds zowel de maximum respons (Trace state = MaxHold) als ook de gemiddelde respons (Trace state = Average) gemeten. Deze staan steeds vermeld bij elk resultaat.
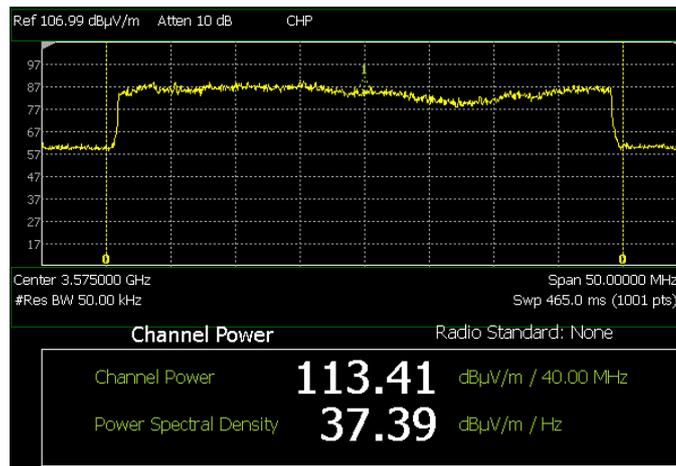
Fig. A.1 3,5 GHz band, MaxHold: 113,41 dBµV/m k.o.m. 0,47 V/m
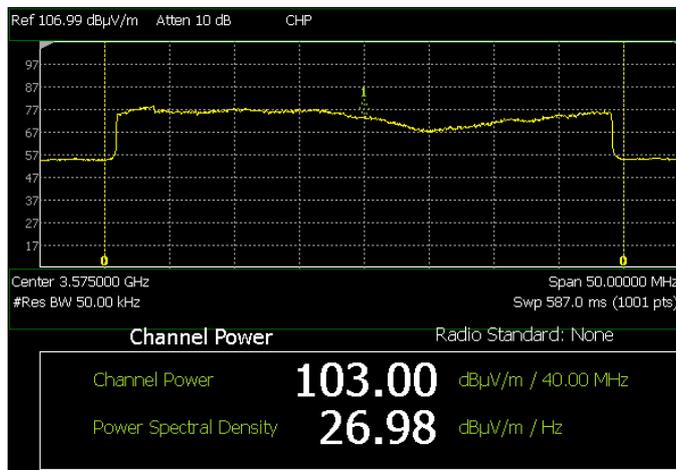
Fig. A.2 3,5 GHz band, Average: 103,00 dBµV/m k.o.m. 0,14 V/m
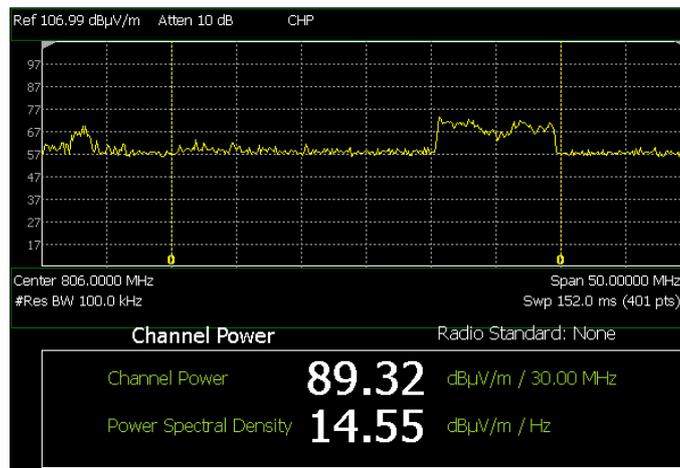
Fig. A.3 800 MHz band, MaxHold: 89,32 dBµV/m k.o.m. 0,029 V/m
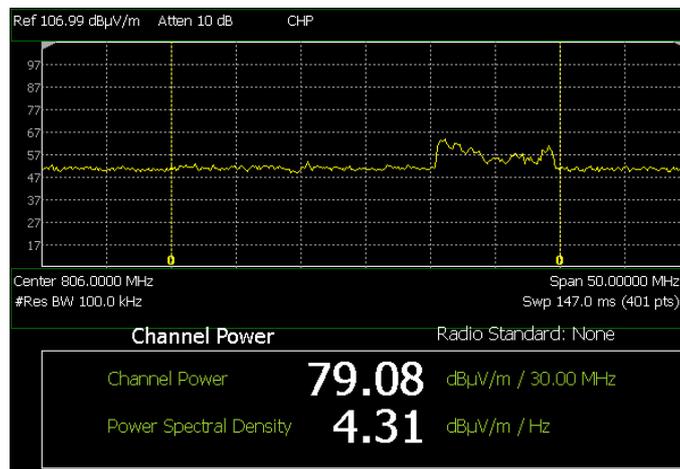
Fig. A.4 800 MHz band, Average: 79,08 dBµV/m k.o.m. 0,009 V/m
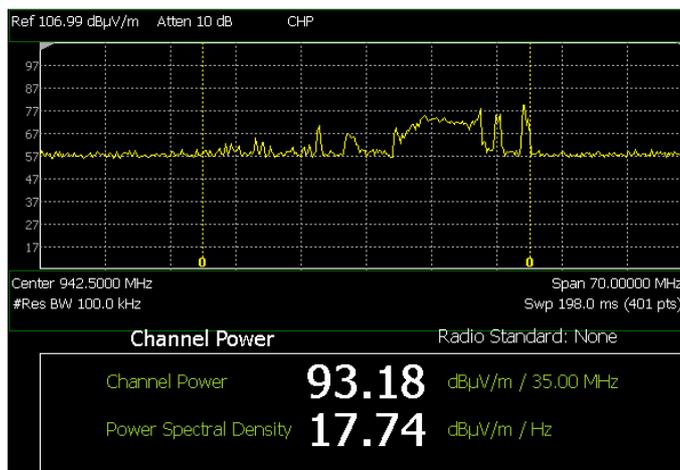
Fig. A.5 900 MHz band, Maxhold: 93,18 dBµV/m k.o.m. 0,046 V/m
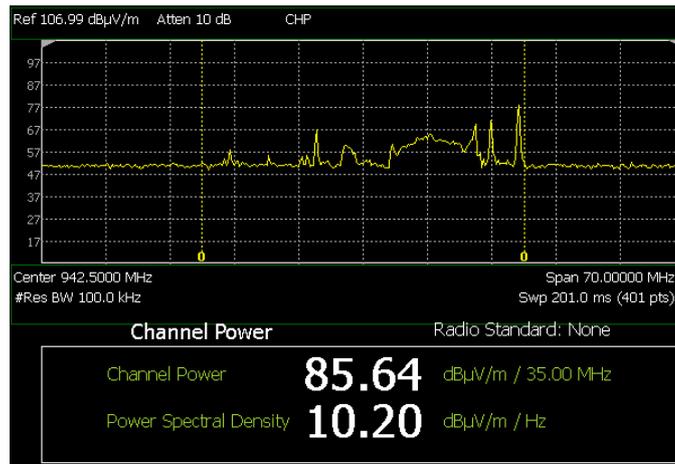
Fig. A.6 900 MHz band, Average: 85,64 dBμV/m k.o.m. 0,019 V/m
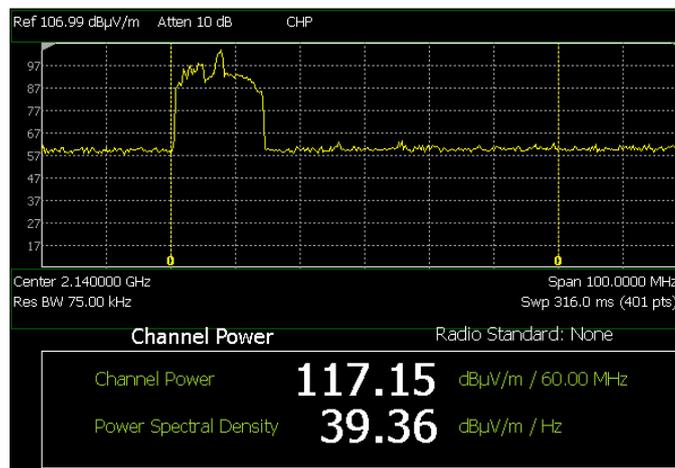
Fig. A.7 1,8 GHz band, Maxhold: 117,15 dBμV/m k.o.m. 0,72 V/m
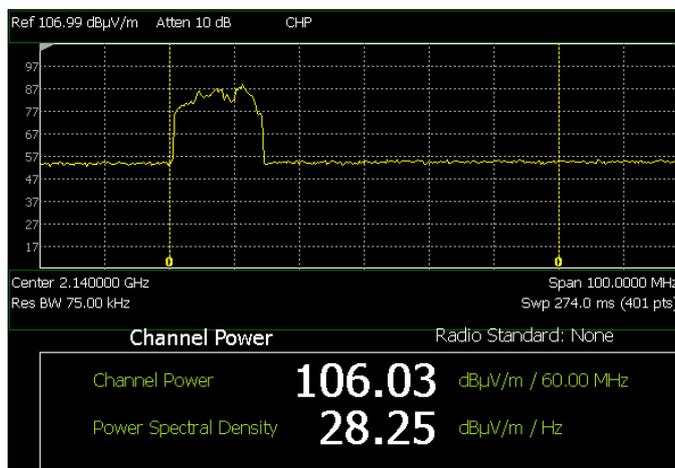
Fig. A.8 1,8 GHz band, Average: 106,03 dBμV/m k.o.m. 0,20 V/m
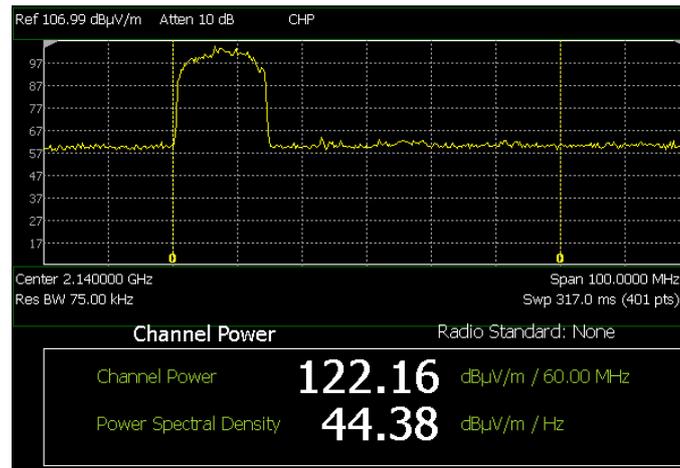
Fig. A.9 2,1 GHz band, MaxHold: 122,16 dBµV/m k.o.m. 1,28 V/m
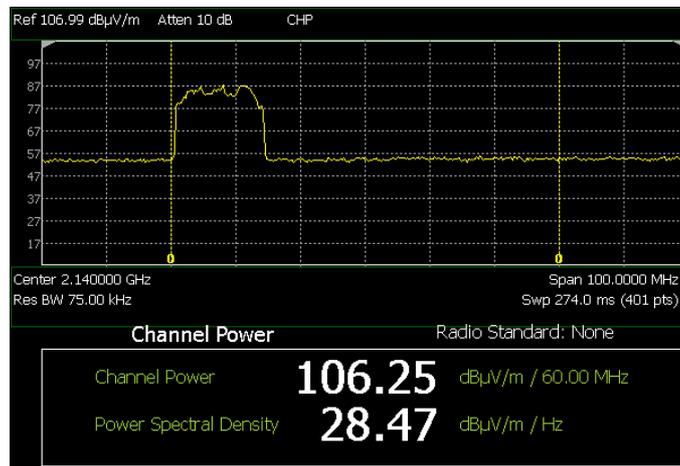
Fig. A.10 2,1 GHz band, Average: 106,25 dBµV/m k.o.m. 021 V/m
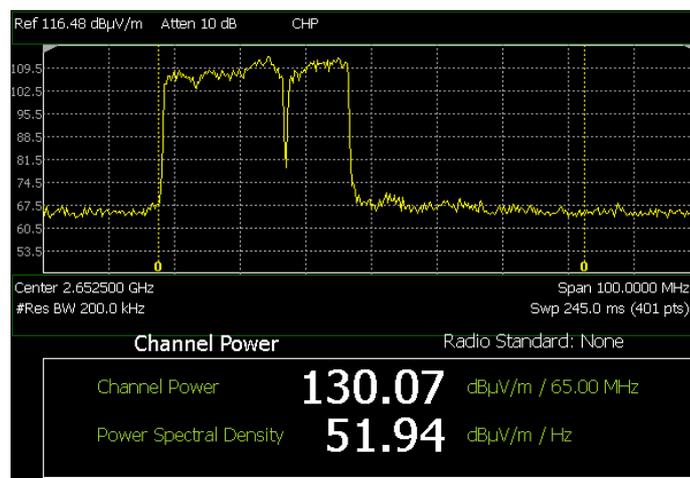
Fig. A.11 2,6 GHz band, MaxHold: 130,07 dBµV/m k.o.m. 3,19 V/m
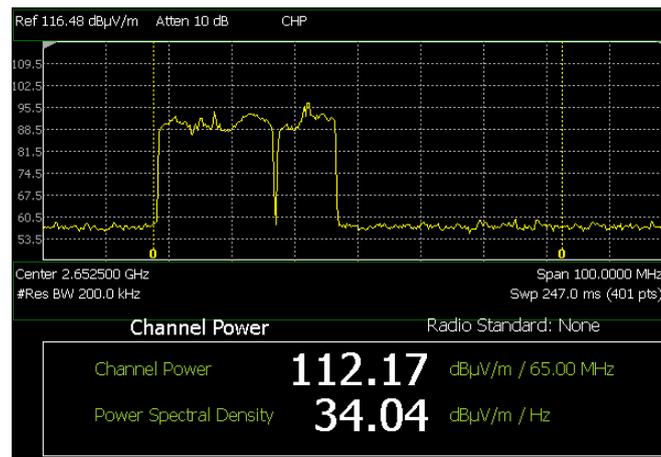
Fig. A.12 2,6 GHz band, Average: 112,17 dBμV/m k.o.m. 0,4 V/m

Appendix B   Meetprocedure

Procedure for the in-situ measurement of electromagnetic fields in the vicinity of various test sites in Eindhoven.

Peter Smulders, Eindhoven University of Technology

Abstract

Eindhoven University of Technology carries out measurements of electromagnetic fields produced by 5G base stations in their vicinity in order to determine their contribution to the total RF electromagnetic field and to examine whether the general public exposure limits are being adhered to. This appendix describes and documents the measurement procedure applied.

1. Introduction

From January 2020 a number of 5G test sites will arise at various locations in the City of Eindhoven. Eindhoven University of Technology (TU/e) wishes to address public concerns about exposure of electromagnetic fields to humans by measuring the electromagnetic fields (EMF) generated by the 5G base stations at these sites at locations where there is access for the general public. The objective of these measurements is to examine how the measured field levels relate to the legal EMF limits (see [1]-[3]) as well as to the total field produced by current generations (2G/3G/4G)mobile systems.

This appendix describes and documents the measurement protocol applied. This measurement protocol is to a certain extend in line with the newest version of CENELEC standard EN 62232, which was published in 2017 [4]. Unfortunately, precise and effective measurement-based assessment methods dedicated to 5G are still being an open problem under evaluation by international organizations [5], [6]. This is because EN 62232 has been originally designed for static wide antenna beams as applied in GSM (2G), UMTS (3G) and LTE (4G) systems rather than for highly focused beams following the specific active users as applied in New Radio (5G) Massive MIMO technology to enable reuse of frequency channels in the space domain. We solve this problem by following a still conservative approach by applying a user equipment device in the direct vicinity of the measurement setup with which we generate maximum downlink traffic thus creating maximum exposure at the measurement position.

2. Base station data collection

In order to allow a computational compliance assessment next to an assessment purely based on measurements, a number parameters of the base station under test should be known. The following data should be provided by the telecom operator:

- Applied transmitter/eNodeB
- Maximum antenna up-tilt
- Maximum antenna down-tilt
- 3 dB beamwidth in the vertical plane

- Horizontal beam steering angle
- 3 dB beamwidth in the horizontal plan (and dependence on steering angle))
- Antenna gain (and dependence on steering angle)
- Polarization angle(s)
- Applied transmit power during the measurement
- Maximum rated transmit power
- Center frequency of the channels and bandwidth
- OFDM subcarrier spacing
- Applied TDD duty cycle during the measurement

3. Measurement equipment

The measurement equipment consists of the following components:

- Keysight FieldFox N9918A handheld RF analyzer
- EMCO 3115 Double-Ridged horn antenna
- Measurement cable HP 85100 60002, nr. 267.

The measurement setup is shown in Fig. B.1.

Fig. B.1 Measurement setup

This measurement setup is used to measure specifically the electromagnetic field generated by the 5G base station under test which implies a frequency-selective measurement in the 3.5 GHz band. The analyzer has a dynamic range of 102 dB and a linearity of 0.66 dB [7]. This complies with the system requirements for frequency selective measurements posed by IEC 62232 [4]. (These requirements read 60 dB and 1.5 dB, respectively.) The expanded uncertainty of the setup is ±2.5 dB as elaborated in Appendix 3 of this report, [8]. This is well within the requirement of the 4 dB posed by [4].

In order to steer the BS antenna beam in the direction of the measurement setup at full transmit power, a data connection is established by using modem-speed test sites. This demands the fully available bandwidth which implies that all resource blocks will become active. A kind of prototype user equipment,

or just a commercial smartphone with broadband speed test app, is used near the measurement antenna to steer the BS antenna beam towards the measurement setup with all resource blocks active.

4. Measurement area selection

The measurements takes place within the domain of investigation (DI) as defined by [4]. The DI is part of the so called assessment domain boundary (ADB) of the base-station under test to which the general public has access. The ADB for the base-station under test is determined following the procedures in [4]. A conservative estimate is a square shaped ADB oriented according to the base station antenna direction with

$$D = 1.3 \sqrt{\frac{\text{EIRP}}{S_{\text{lim}}}} \quad , \tag{1}$$

with D the side length of the ADB (in meters) in the mean beam direction, EIRP the effective isotropic radiated power and S_{lim} representing the exposure limit, see Fig. B.2.
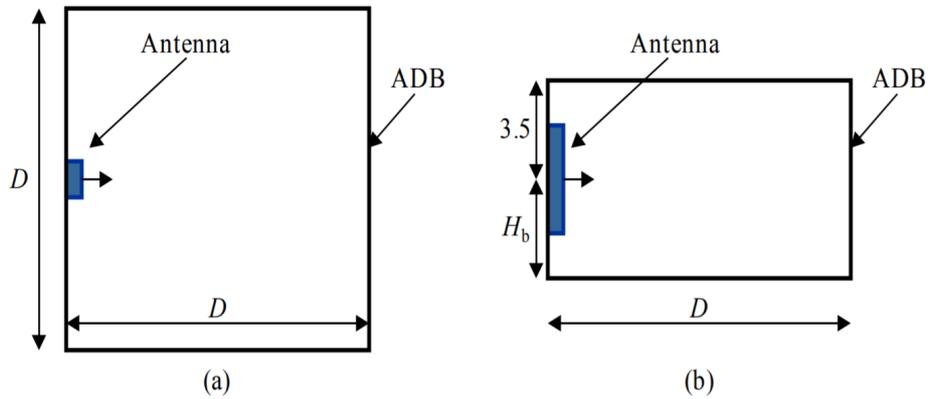
Fig. B.2 (a) Top-view of the square-shaped assessment domain boundary (ADB) with side length D, (b) Side-view of the ADB determined according to [4]

5. Measurement position selection

The probable position of maximum exposure to EMF associated with an antenna main lobe for line-of-sight scenarios is estimated based on the well-known two-ray ground reflection model and equation [9]:

$$X_{max}^{exp} = \frac{1}{2} \left(\sqrt{\left[(H-h)\left(1+\frac{q}{2}\right)\tan(\alpha) \right]^2 + 2q(H-h)^2} - (H-h)\left(1+\frac{q}{2}\right)\tan(\alpha) \right) , \tag{2}$$

where X_{max}^{exp} (in meters) indicates the estimated horizontal distance from the antenna in the direction of the main lobe where maximum exposure is expected, H represents the height of the base station antenna (in meters), h is the height of the measurement antenna (in meters), α is the base station antenna down-tilt and q is determined by:

$$q = \frac{\log(0.5)}{\log\left[\cos\left(\frac{\theta_{bw}}{2}\right)\right]} \quad , \tag{3}$$

where θ_{bw} is the antenna half-power beamwidth in the vertical plane. Eq. (2) is thus based on the assumption that the base station antenna beam has a fixed down-tilt. In case of beam-steering in elevation, i.e., in case the beam is not fixed but always directed towards the measurement position, the two-ray ground-reflection model must be applied, accordingly.

The estimated position X_{max}^{exp} indicates the probable position of the maximum exposure. Nevertheless, it must be taken into account that scattered and diffracted fields may shift the real maximum in other regions. Therefore, the measurement setup is attentively moved in the horizontal and vertical plane within the DI to locate the position of the maximum exposure as recommended in [10]. During the search for this position, the RF analyzer may be equipped with an antenna with better form factor and isotropy.

Massive MIMO base stations direct a narrow beam towards each active user. To arrange that maximum power is received at the measurement position, a 5G user equipment device is used in the immediate vicinity of the measurement setup to generate download traffic at the maximum speed.

6. Measurement method

Measurements are performed at the point of maximum exposure according to the following steps:

- The RF analyzer is connected to the measurement antenna via the measurement cable.
- The RF analyzer is switched on and put in Spectrum Analyzer mode with calibrations and corrections for the antenna factor and to take into account the losses in the measurement cable.
- The RF analyzer is put in Power Measurement mode with the following settings:
    - Center frequency and integration bandwidth (i.e., channel bandwidth) according to data provided by the operator,
    - Resolution bandwidth times number of (equidistant) frequency points taken larger than frequency span,
    - Averaging number is low (10 to 20),
    - Detection Method on Average (RMS)
    - The measurements display maximum response (Trace State = MaxHold). In addition, measurements displaying average response (Trace State = Average) may be performed.
- The measurement antenna is turned in azimuth and elevation and also rotated around its axis until the maximum field level is measured.
- Averaging number is increased so that averaging number times frequency sweep becomes larger than 6 minutes.
- The BS antenna beam is steered in the direction of the measurement setup at full transmit power.
- As a conservative approach, the E-field in the allocated 5G frequency band is measured with Trace State = MaxHold within a measurement time of 6 minutes:
- For comparison with current generations, also the E-field in the following bands is measured:
    - 791 – 821 GHz
    - 925 – 960 GHz
    - 1805 – 1875 GHz
    - 2110 – 2170 GHz
    - 2620-2685 GHz
- Eventually, the measurements are repeated for other directions and orientations of the antenna where significant contributions are measured and the E-field is post-processing according to [4]

per measured frequency band to determine the total E-field as the result of power coming from all directions.

7. Reporting

For each measurement session carried out at a 5G pilot location a measurement report is written. This measurement report contains:

General data
- Objective of measurement
- Motivation of measurement
- Date of measurement
- Location/address of measurement
- Date of report
- Eventual Remarks

BS antenna data
- Address base station site
- Location
- Height
- GPS coordinates
- Type
- Transmitter eNodeB
- Direction
- Frequency band
- Gain
- Power
- Eventual remarks

Applied measurement equipment and method
- List of applied measurement equipment/components including series numbers
- Applied measurement method
- Type of measurement (broadband or selective)
- Measurement uncertainty in terms of dB as well as in terms of percentage
- Eventual remarks

Description of the measurement location
- Map on which the base station as well as the measurement setup is indicated
- Explicit description of objects in the environment that could significantly influence the measurement results
- Accessibility of the location for the general public
- Duration of the exposure
- Picture of base station antenna, measurement setup and environment
- Eventual remarks

Position of the measurement antenna
- GPS coordinates of the measurement antenna
- Height of the measurement antenna

- Distance of measurement antenna from base station antenna
- Eventual remarks

Measurement results

- Measured maximum value (Trace State = MaxHold) of the E-field (V/m) for each measured frequency band
- Maximum values are derived from these measured values to include measurement uncertainty
- Eventual additional remarks

Conclusion

- Maximum aggregate exposure as a result of all systems 2G/3G/4G/5G together as compared to the ICNIRP exposure limits
- Maximum contribution of the 5G part to this level of total exposure.
- Eventual additional remarks

8. Conclusion

TU/e carries out measurements of electromagnetic fields produced by various test sites in Eindhoven in their vicinity in order to determine their contribution to the total RF electromagnetic field and to examine whether the general public exposure limits are being adhered to. This appendix describes the measurement protocol applied. The measurement protocol is as much as possible in line with CENELEC standard EN 62232 *Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*. However, this standard has been originally designed for static wide antenna beams rather than for concentrated antenna beams dynamically directed towards active users as applied in 5G Massive MIMO technology. We solve this problem by applying a user equipment device in the direct vicinity of the measurement setup with which we generate maximum downlink traffic thus creating maximum exposure at the measurement position.

References

[1]   International Commission on Non-Ionizing Radiation Protection: *Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields*. Health Physics 74:494-522, 1998.

[2]   European Union Council Recommendation of 12th July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) (1999/519/EC).

[3]   https://www.rijksoverheid.nl/documenten/rapporten/2018/07/03/actieplan-digitale-connectiviteit

[4]   CENELEC standard EN 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*, 2017. Available at www.cenelec.eu.

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Appendix C   Meetonnauwkeurigheid

Evaluation of uncertainty in the in-situ measurement of electromagnetic fields from 5G pilot locations

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Abstract

Eindhoven University of Technology carries out measurements of electromagnetic fields produced by 5G base stations from various test sites in the City of Eindhoven in order to determine their contribution to the total RF electromagnetic field and to examine whether the general public exposure limits are being adhered to. The estimation of uncertainty in these measurements is in particular crucial in the cases where measured values are close to the safety limit. The uncertainty sources are explained and an uncertainty budget is presented.

1. Introduction

From January 2020, a number of 5G test sites will arise at various locations in the City of Eindhoven. Eindhoven University of Technology (TU/e) addresses public concerns about exposure of electromagnetic fields to humans by measuring the electromagnetic fields (EMF) generated by the 5G base stations at these sites at locations where there is access for the general public. The objective of these measurements is to examine how the measured field levels relate to the legal EMF limits as well as to the total field produced by current generations (2G/3G/4G) mobile systems.

In 1998, the International Commission on Non-Ionizing Radiation (ICNIRP) has issued limit values for the protection of people from electric, magnetic and electromagnetic fields [1]. In 1999, The Council of the European Union issued a recommendation, adopting these ICNIRP's limit values [2]. Although this recommendation is not binding it is set in Dutch law; just as the current mobile networks the 5G-network has to meet the international EMF exposure limits [3].

An important element to be considered in performing EMF measurements is the uncertainty of the measurement result. In particular in case where a measured value is lower than, but close to the safety limit, the measurement uncertainty must be estimated as accurately as possible to ensure that the exposure is indeed lower than the limit. The uncertainty evaluation given below is in line with the ISO/IEC Guide to the expression of uncertainty in measurement [4], the CENELEC Basic standard on measurement and calculation procedures for human exposure to EMF, EN50413 [5] and the CENELEC standard on the determination of RF field strength in the vicinity of base stations, EN62232 [6].

2. Terms and basic concepts specific to the analysis of uncertainty in this appendix.

Concepts and basic metrological terms relevant for the uncertainty estimation under consideration are a subset of those listed in [4]. This subset can be listed as follows:

Measurement – set of operations having the object of determining a value of a quantity

Measurand – Particular quantity subject to measurement

Probability – a real number in the scale 0 to 1 attached to a random event

Probability distribution (of a random variable) – a function giving the probability that a random variable takes any given value or belongs to a given set of values.

Arithmic mean average – the sum of values divided by the number of values

Variance – a measure of dispersion, which is the sum of the squared deviations of observations from their average divided by one less than the number of observations.

Standard deviation – the positive square root of the variance

Uncertainty (of measurement) – Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty – Uncertainty of the result of a measurement expressed as a standard deviation.

Confidence level – The probability that the true value is within the given uncertainty limit.

Normal distribution – Gaussian shaped distribution which can be assigned to uncertainties derived from multiple uncertainty contributions. The standard uncertainty for a value of uncertainty with assumed normal distribution is given by dividing the value of uncertainty U_i by a factor k, appropriate to the level of confidence:

$$u_i = \frac{U_i}{k}$$

For a reported confidence level of 95%, the factor k = 1.96 or approximately 2.

Rectangular distribution – In this distribution there is equal probability of the true value lying anywhere between the prescribed limits. A rectangular distribution should be assigned where a manufacturer's specification limits are used as the uncertainty, unless there is a statement of confidence associated with the specification, in which case a normal distribution can be assumed. For rectangular distributions the standard uncertainty results to:

$$u_i = \frac{U_i}{\sqrt{3}}$$

where U_i represents the semi-range limit value of the specific uncertainty contribution.

U-shaped distribution – The U-shaped distribution is a function that represents outcomes that are most likely to occur at the extremes of the range. As such it forms the shape of the letter "U". For U-shaped distributions the standard uncertainty results to

$$u_i = \frac{U_i}{\sqrt{2}}$$

Combined standard uncertainty – The combined uncertainty u_c is obtained by taking the square root of the sum of squares of the individual standard uncertainties. Any contributions with known or suspected adverse correlation should be added together. Then for *n* contributions

$$u_c = \sqrt{\sum_{i=1}^{n} u_i^2}$$

Coverage factor – Numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

E**xpanded uncertainty** – The expanded uncertainty, U_e, defines an interval about the measured result that will encompass the true value with a specified level of confidence, *p* %. The expanded uncertainty is obtained by multiplying the combined standard uncertainty by coverage factor *k*, thus:

$$U_e = k u_c$$

The recommended level of confidence is 95 %, which can be obtained with *k* = 1.96.

Repeatability – Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of the measurement. These repeatability conditions include:
- The same measurement procedure
- The same observer
- The same measuring instrument, used under the same conditions
- The same location
- Repetition over a short period of time

Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

4. Estimation of uncertainties in the selective measurement of electric fields in the 3.5 GHz frequency band with RF spectrum analyzer and directional antenna.

The uncertainty estimation provided herewith is related to the measurement of the amplitude of the electric field component performed with a Keysight FieldFox handheld RF analyzer, an EMCO 3115 Double-Ridged horn antenna interconnected via a 90 cm long cable HP 85100 60002 nr. 267. The total measurement setup is shown in Fig. C.1.

Fig. C.1 Measurement setup

In what follows we describe the estimation of the components that contribute most significantly to the measurement uncertainty budget considering the widest reasonable ranges of input variables of the measuring system.

Analyzer amplitude uncertainty – The analyzer is able to make channel power measurements with an uncertainty figure of 1.00 dB within a temperature range of -10 to 55° C [7]. This figure includes frequency response, input attenuation, IF-amplifier and temperature response uncertainties. No warm-up required. A prerequisite of the mentioned amplitude uncertainty figure is that the instrument is within its calibration cycle which is the case [8].

Antenna calibration uncertainty – The EMCO Model 3115 Double Ridged Waveguide Antenna is a linearly polarized broadband antenna covering the frequency range of 700 MHz to 18 GHz. This antenna was designed and built specifically for EMI measurements and specifications compliance testing. It is precision machined and individually calibrated during the manufacturing process. Apparent gain at 1.0 meter from the end of the antenna is determined and included in its manual together with the corresponding antenna factor [9]. We recently verified these antenna factor data by measuring the antenna gain in our anechoic room giving a match for each listed frequency within 1 dB.

Mismatch uncertainty – Mismatch uncertainty arises from an incomplete knowledge of the phases of the reflection coefficients of the source and load impedances plus their interconnection. The limit value for the mismatch uncertainty associated with the power transfer at a junction is obtained from

$$U_i = 20\log(1 \pm |\Gamma_G||\Gamma_L|) \quad \text{dB}$$

in which Γ_G and Γ_L represent the reflection coefficients for the source and load. In our measurements we reduce mismatch to a minimum by taking measures as using a torque wrench for consistency and using good quality cable as listed in [6]. Therefore both reflection coefficients are expected to be small (<<1).

With assumed worst-case values of Γ_G = 0.1 and Γ_L = 0.1 the mismatch uncertainty becomes as low as 0.09. The U-shaped distribution is applicable to mismatch uncertainty [10].

Repeatability uncertainty – 10 repeated measurements revealed a standard deviation of 1 dB. Note, that this figure also represents the standard uncertainty without the need to apply a division factor.

The uncertainty budget is summarized in Table C.1. Since all the uncertainty components can be considered unrelated, the value of the combined uncertainty is obtained by adding them as root mean square values.

Table C.1: Uncertainty budget for the 5G field strength measurements.

Component	Influence factor	Specific Uncertainty [dB]	Probability Distribution	Division factor	Standard Uncertainty [dB]
Analyzer	Amplitude uncertainty	1.0	Rectangular ($k\approx1.73$)	1.73	0.58
Analyzer	Display reading uncertainty	0.05	Rectangular ($k\approx1.73$)	1.73	0.03
Cable	Calibration uncertainty	0.1	Normal ($k\approx2$)	2	0.05
Cable	Attenuation frequency interpolation	0.05	Rectangular ($k\approx1.73$)	1.73	0.03
Antenna	Calibration uncertainty	1.0	Normal ($k\approx2$)	2	0.50
Antenna	Antenna factor frequency interpolation	0.1	Rectangular ($k\approx1.73$)	1.73	0.06
Mismatch	Reflections	0.09	U-shaped ($k\approx1.41$)	1.41	0.06
Repeatability	Limited Repeatability	1.0	Normal	-	1.0

Combined standard uncertainty [dB]:	1.26
Coverage factor (95% confidence level):	1.96
Expanded uncertainty [dB]	2.47
Expanded uncertainty [%]	32.9

5. Conclusion

TU/e carries out measurements of electromagnetic fields produced by 5G base stations in their vicinity in order to determine their contribution to the total RF electromagnetic field and to examine whether the general public exposure limits are being adhered to. The uncertainty budget has been determined which yields an expanded uncertainty of ±2.5 dB or 33% for a 95% confidence level.

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