RESEARCH ARTICLE

Application of the Maximum Power Extrapolation Procedure for Human Exposure Assessment to 5G Millimeter Waves: Challenges and Possible Solutions.

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ABSTRACT This paper describes an investigation on the application of the Maximum Power Extrapolation (MPE) technique on a fully operational Fixed Wireless Access (FWA) FR2-band 5G gNB. The data was acquired in [27.1-27.3] GHz band using a network scanner over nearly 10 minutes periods to allow a statistical analysis and an accurate estimation of the role of each contribution to the total uncertainty, including the fading affecting the 5G FR2 reference signal. The results show that the level of the electromagnetic field is well below the limits imposed by Italian legislation. However the goal of the paper is more fundamental, and shows an approach that can be used to identify the critical elements of the measurement set-up, suggesting where to concentrate efforts to improve the measurement procedure. In particular, the uncertainty budget highlights three contributions, (i.e. estimation of the traffic beam level, of the probe response and of the 5G FR2 reference signal) that deserve further investigations.

INDEX TERMS Human exposure assessment, maximum power extrapolation, 5G antennas, cellular systems.

I. INTRODUCTION

Field level measurement for human exposure assessment is an important issue in the communications engineering community.

Research on biological effects of radiofrequencies is a very active field of research. The results of the researches are analyzed by the International Commission on Non Ionizing Radiation Protection (ICNIRP) [1], that gives guidelines on

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limiting exposure to electromagnetic fields for the protection of humans exposed to radiofrequency electromagnetic fields up to 300 GHz.

ICNIRP recently published updated guidelines, in terms of basic restrictions and reference levels of many different quantities (Specific Absorption Rate (SAR), absorbed energy density, incident field, incident power density, etc.) depending on the frequency range, on the observation time and on the exposed people. Such guidelines were assessed by ICNIRP according to the review of available literature on biological and health effects related to temperature rise.
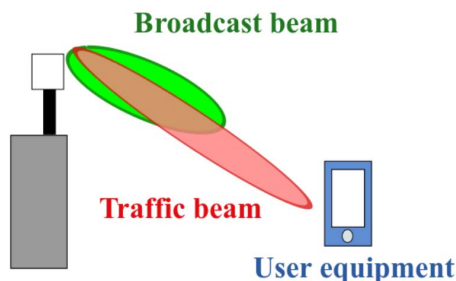
FIGURE 1. gNB uses two sets of beams, broadcast beams and traffic beams. SS-PBCH channel is transmitted on broadcast beams, while specific-user data are transmitter on traffic beams.

These indications are the basis for national regulations, that can be also more restrictive.

Loosely speaking the guidelines require observation of the field over an adequate time window to obtain an estimate of the energy associated with the electromagnetic field.[1] The observation time generally ranges from 6 to 30 minutes [1].

The observation window can be shortened using MPE [2] techniques. Such techniques allow to estimate the maximum field level from data acquired in a short time window assuming that all the resources of the communication system are assigned to a single user. Consequently, they give an upper bound of the field level in the measurement position. The value obtained from MPE procedures must subsequently be multiplied by an appropriate correction factor taking into account the stochastic nature of the communication in order to obtain a realistic value of the field level [3], [4], [5], [6], [7], [8].

The first step of the roll-out phase of 5G networks has involved Base Stations (BSs) working in Frequency Range 1 (FR1) band. Many effective solutions for 5G MPE in FR1 have been proposed in the literature [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], which allow the accurate assessment of the field level at the measurement point in currently used 5G systems.

While many measurement campaigns for validation of MPE techniques in FR1 band are discussed in the open literature, at the best knowledge of the authors only a few papers present measurements in Frequency Range 2 (FR2) [19], [20], [21], [22], [23].

Indeed, the deployment of FR2 was slow, both due to the complexity of millimeter wave technology, and to the absence until now of a "killer application" that represents the trigger for the deployment of this technology.

FWA is an efficient alternative to wired connections with data rate competitive with Fiber-To-The-Home (FTTH) solutions without the costs associated with the last mile involved in fixed access deployments. There is therefore a great interest in FWA systems as key technology able to reduce

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[1]International guidelines also require the spatial average of the field, which is not the focus of this article.

FIGURE 2. Roof-top FR2 gNB.

FIGURE 3. Map of measurement zone; white circle A: gNB position; yellow circle B: measurement position; the figure shows also the area covered by the three beam gNB sectors.

the digital divide in rural communities helping to reach the ambitious goal of the European Digital Agenda program, i.e. providing the entire population with the possibility of accessing the Network through high-speed connectivity services.

The current step of the roll-out phase of 5G networks in Italy is involving BSs working in FR2 band, mainly for FWA applications. This gave us the chance to carry out measurements in full operational conditions. The aim of this paper is to describe the results of the MPE technique to estimate the maximum field level radiated by the gNB.

The description of 5G frame is present in many books and papers, besides the 3rd Generation Partnership Project (3GPP) documentation [24], and will not be repeated here. A simple introduction limited to the concepts useful for the MPE technique is discussed for example in [12] and [14].

This paper describes an investigation on the application of the MPE technique on a fully operational FWA FR2-band 5G gNB.

The results show that the level of the electromagnetic field is well below the limits imposed by Italian legislation. However the goal of the paper is more fundamental, and shows

an approach that can be used to identify the critical elements of the measurement set-up, suggesting where to concentrate efforts to improve the measurement procedure.

The paper is organized as follows: in Section II a quick overview of MPE for 5G is given. Section III is devoted to the description of the measurement campaign, whereas in Section IV the MPE is applied to the measurements. Conclusions are drawn in Section V.

II. THE MAXIMUM POWER EXTRAPOLATION TECHNIQUE FOR 5G

The goal of the Maximum Power Extrapolation procedure is the estimation of the maximum field level [V/m] that could be obtained at the measurement point.

Although methods that allow to avoid the use of a reference signal have been recently proposed [14], standard MPE procedure requires the estimation of a reference quantity that is a cell specific signal always "on air" and transmitted at maximum power. The standard reference signal adopted in 5G MPE is related to Synchronization Signal/Physical Broadcast CHannel (SS/PBCH) [12]. In particular, we selected the average field level of the Resource Elements (REs) of the highest Synchronization Signal Block (SSB) received in the measurement position (in the following E_{SSB}). SSBs are periodically transmitted using *broadcast* beams (Fig. 1).

Instruments usually give the power level at the instrument input connector P_{SSB}. From the knowledge of this value, of Antenna Factor (AF) [25] and of the power losses α of the cable connecting the antenna to the receiver, it is possible to obtain the field level:

$$E_{SSB} = \sqrt{\frac{P_{SSB} Z_{in}}{\alpha}} AF \qquad (1)$$

wherein Z_{in} is the input impedance of the instrument.

The maximum field level E_{5G}^{max} can be estimated as:

$$\bar{E}_{5G}^{max} = E_{SSB} \sqrt{N_{SC}} \sqrt{F_{TDC}} \sqrt{F_{beam}} \qquad (2)$$

wherein N_{SC} is the number of subcarriers in the whole frequency channel, F_{TDC} is the duty cycle when TDD multiplexing is used and F_{beam} is the ratio between the traffic beam and the broadcast beam in the measurement direction.

In fact, most of radio resources are used for user traffic data, that are transmitted using traffic beams (Fig. 1). Since traffic beams have higher gain compared to broadcast beams, the REs of the user traffic data have higher power compared to the ones used in SSBs. F_{beam} is the boosting factor taking into account such gain difference [12].

F_{beam} can be obtained from measurement, observing traffic data by waterfall reconstruction [10] in a sufficiently long time interval, or using a User Equipment (UE) able to force the traffic toward the measurement position [12]. Furthermore, an estimation of F_{beam} can also be obtained by the
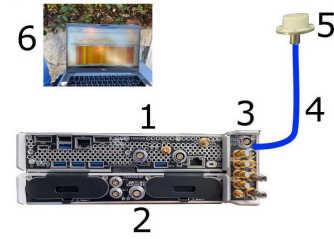

FIGURE 4. Measurement set-up. 1) Rohde & Schwarz TSMA6B mobile network scanner. 2) TSMA6B-BP battery pack. 3) Rohde & Schwarz TSME30DC downconverter. 4) coaxial cable. 5) Antenna steatite Q-Par. 6) Laptop running Rohde & Schwarz Romes 4 software.

FIGURE 5. Measurement position. The gNB is on the roof of the house on the right.

Broadcast Envelope Radiation Pattern (BERP) and the Traffic Envelope Radiation Pattern (TERP) [26].[2]

The above described MPE procedure is based on the structure of the signal frame. The differences between FR1 and FR2 frames involve mainly the numerology and the number of SSBs in Burst, and do not impact on the MPE procedure. Consequently, it can be applied without modifications to FR2.

III. MEASUREMENTS

In this Section the relevant information related to the measurement campaign is given, as well as a statistical analysis of the acquired data.

A. MEASUREMENT SITE

The measurement site is placed in Guidonia Montecelio, a medium-size town ($\simeq$ 87000 inhabitants) north-east of Rome (Italy). The FR2 gNB (see Fig. 2) was on a two floors building, at an height of approximately 14.5 m. The measurement position was at almost 100 meters from the gNB. The communication was in Line of Sight (LOS) condition.

The measurement area is typically suburban with a building structure consisting mainly of low-rise houses (see Fig 3).

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[2]The Envelope Radiation Pattern is defined [26] as "a non-physical radiation pattern obtained by taking, for each direction in azimuth and elevation, the maximum of the absolute, not peak normalized to its own peak, radiation pattern among the radiation patterns that the Active Antenna System can generate for a given operating condition (deployment/coverage scenario)."
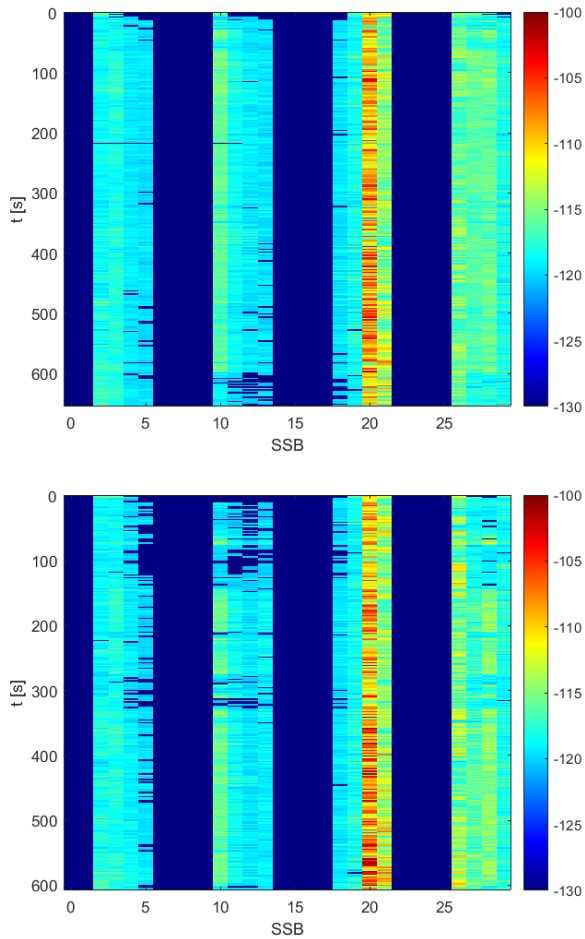
FIGURE 6. Measured values of the SSS-RePower of the SSBs [dB]. Top figure: first data set; bottom figure: second data set.
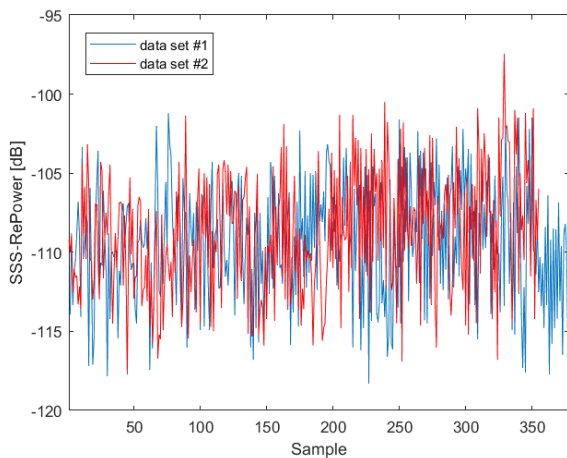

FIGURE 7. Measured value of the SSS-RePower [dB] of the 20th SSB. Blu line: first data set; red line: second data set.

B. MEASUREMENT SET UP

The measurement set up was based on a Mobile Network Scanner [27]. The measurement chain is shown in Fig. 4 and consists of:
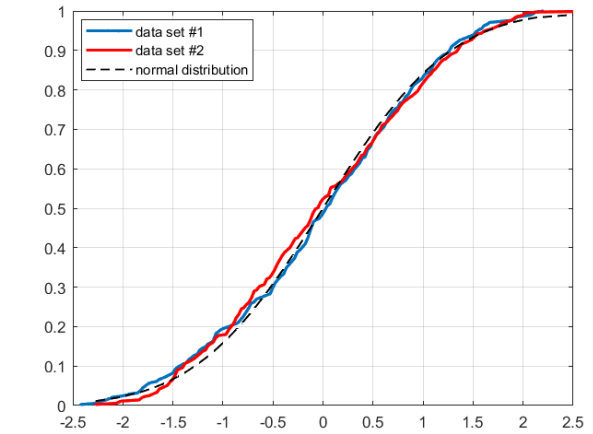

FIGURE 8. Empirical CDF of the Z-transform of the SSS-RePower [dB]. Blue: first data set; red: second data set. Black dashed line: normal distribution.

1) Rohde & Schwarz TSMA6B Mobile Network Scanner;
2) TSMA6B-BP battery pack;
3) Rohde & Schwarz TSME30DC ultracompact downconverter 24 GHz - 30 GHz input band;
4) coaxial cable (length 1.35 m);
5) antenna Steatite Q-Par, Linear-polarized, Omnidirectional, 26 GHz - 40 GHz band, maximum external diameter 46 mm;
6) laptop running Rohde & Schwarz Romes 4 software.

The antenna was placed in LOS with the gNB, in the position shown in Fig. 5. The figure also shows some obstacles that are close to the LOS.

C. ACQUISITION AND DATA ANALYSIS

Before discussing the application of MPE procedure in next Section, it is useful to enter into some details regarding the acquired data.

The network scanner used during the measurement campaign gives some parameters directly related to the power of the REs of the SSB. One of them is SSS-RePower, that is the average power of resource elements of Secondary Synchronization Signal (SSS) in the SS/PBCH block. This is a quantity suitable for the MPE procedure. Accordingly, we use the SSS-RePower of the SSB received at maximum power as reference value. Two different acquisitions were carried out: first 378 samples were acquired over a period of 654 s; then other 355 samples were acquired over a period of 607 s. Both sample sequences were not uniformly acquired, with a time step less than 5 s.

The area served by the gNB is divided into three sectors. In Fig. 6 the SSS-RePower of the sector in which the measurement position is placed is shown as a function of time (vertical axis) for all the SSBs of 5G frame (horizontal axis). We can note that the SSB are organized in groups of four. The SSB associated to the broadcast beam pointing toward the measurement position is easily identifiable as being #20,

Data set	Mean [dB]	Standard Deviation	Number of samples
#1	-109.35	3.69	378
#2	-108.81	3.91	355

due to the higher average level of the REs associated to it. This column contains the data that will be object of analysis.

The SSS-RePower [dB] measured samples of the 20th SSB are plotted in Fig. 7 for both data sets. The plot shows quite a large variation of the measured values.

The variation of the reference signal used in MPE is not a new phenomenon, and is subject of an active research [28], [29]. However, due to the absence of 5G FR2 gNB, the studies have been carried out mainly on 4G and 5G in FR1. Consequently, in the following the data will be analyzed in detail.

Considering the data in dB, the CDF of transformation $Z = (x - \hat{x})/\hat{\sigma}$, x being SSS-RePower samples, $\hat{x}$ and $\hat{\sigma}$ the estimated average and standard deviation respectively (summarized in Table 1), is shown in Fig. 8 as blue and red lines. The shape strongly resembles the normal distribution, plotted in the same Figure as black dashed line. This heuristic observation is confirmed by the Kolmogorov-Smirnov hypothesis test that gives a quite high *p*-value (*p*-value = 0.49), consistent with the null hypothesis.

This result poses a number of questions. First of all, are these variations related to a variation of the incident field level or to uncertainties of the measurement chain? This requires a detailed analysis of the contribution to uncertainty of the whole measurement channel to identify possible causes of large random variations. Such an analysis will be carried out in the next Section. Indeed, mismatch uncertainty associated to cables working at high frequency can give a fast variation of the measured signals if the cables are long compared to the wavelength, can be bent and have bad phase-stability. However, during the measurements the cables were fixed, and in any case the mismatch uncertainty turns out to be quite small. Loosely speaking, the analysis of the measurement chain will show an uncertainty level incompatible with the large variations of the signal. Our conclusion is that they reflect a phenomenon associated to the incident field.

A further interesting observation is that the distribution is Gaussian in logarithmic scale, i.e. the natural values follow a Log-normal distribution. As well known, Log-normal distributions approximate the product of many independent random contributions.

Variation of the signal versus time is a phenomenon known as fading [30]. Usually, fading is divided in "fast fading" and "slow fading". The former is caused by fast phase variations of the incident signal in presence of multipath, and has a Rayleigh distribution when there is no LOS path, or a Rice distribution when it is present. Slow fading is caused by 'macroscopic' variations of the environment geometry, e.g. due to the variation of the percentage of urbanization and typology of the buildings in different areas of the town, and follows a Log-normal distribution. Accordingly,
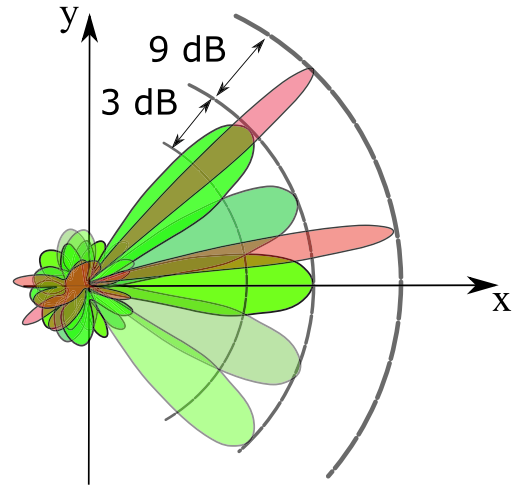

FIGURE 9. Green: set of broadcast beam covering the sector of interest; red: broadcast beams pointing toward two possible users.

the distribution of measured samples seems to match a slow fading-like phenomenon, that however does not have simple physical explanations in the conditions of the measurements carried out.

IV. EVALUATION OF MAXIMUM FIELD
In this Section the MPE is applied to measured data described in previous Section. The procedure is explained step by step, and the uncertainty of each contribution is calculated in last subsection.

A. PARAMETERS REQUIRED FOR THE MPE PROCEDURE
As a preliminary step, some information on the signal object of measurement was obtained from both the operator and the network scanner.

The licensed band assigned to the mobile phone operator is [27.1-27.3] GHz, divided into two equal sub-bands, used in carrier aggregation.

The numerology adopted in the frame is $\mu = 3$. Accordingly the subcarrier spacing is $15 \times 2^{\mu} = 120$ KHz. From these data it is possible to estimate the number od subcarriers. Due to carrier aggregation, the total bandwidth is 200 MHz, leading to a total number of subcarriers equal to:

$$N_{SC} = \frac{200 \times 10^6}{120 \times 10^3} = 1667 \quad (3)$$

The Gain (2.6 dB) indicated by the vendor [31] allows to evaluate the Antenna Factor AF (at center band) as:

$$AF = \sqrt{\frac{\eta}{Z_0} \frac{4\pi}{\lambda^2 G}} = 654.23 \quad m^{-1} \quad (4)$$

wherein $\eta = 377 \ \Omega$ is the free space impedance, and $Z_0 = 50 \ \Omega$ is the input impedance of the downconverter.

The value of the F_{TDC} is standard, and equal to $F_{TDC} = 0.743$.

The value of power losses of the cable 4 was provided by the vendor of measurement equipment, and is equal to $\alpha = -3.2$ dB.

Estimation of the F_{beam} represents a critical point. As previously noted, F_{beam} can be estimated by measurements with a quite good accuracy. However, this requires a Scalar Spectrum Analyzer [10] or a Signal Analyzer [12] able to cover FR2. Such equipment was not available during the measurement campaign. The remaining option is to use information on the radiation patterns of the broadcast and traffic beams. However, these data were not available, and information was limited to the maximum gain of the patterns of traffic and broadcast beams. In order to obtain an estimate of F_{beam} we made an educated guess on the patterns. First of all, the connection is in LOS at a distance (almost 100 m) sufficient to accept the far field condition. We assume that the traffic beam is able to point its maximum toward the measurement position. Regarding the broadcast beams, we suppose that the set of beams used to cover the sector overlap at 3dB. This scheme gives a value of F_{beam} ranging from 9 dB to 12 dB (see Fig. 9). Accordingly. we consider a rectangular distribution of F_{beam} from 9 to 12 dB with an estimated average value of 10.5 dB.

B. FIELD LEVEL FROM MPE PROCEDURE

At this point, we have all the parameters required by Eq. 1 and 2.

Regarding Eq. 1, the mean is estimated in Watt for both data sets as:

$$P_{SSB} = 10^{\hat{x}/10} = \begin{cases} 1.16 \times 10^{-14} \text{ W} & dataset \ \#1 \\ 1.32 \times 10^{-14} \text{ W} & dataset \ \#2 \end{cases} \quad (5)$$

and the corresponding field level of SSB is

$$E_{SSB} = \sqrt{\frac{P_{SSB} Z_{in}}{\alpha}}$$

$$AF = \begin{cases} 7.21 \times 10^{-4} \text{ V/m} & dataset \ \#1 \\ 7.67 \times 10^{-4} \text{ V/m} & dataset \ \#2 \end{cases} \quad (6)$$

Finally, the best estimate of maximum mean value of the electric field can be extrapolated from Eq. 2 as

$$\bar{E}_{5G}^{max} = E_{SSB} \sqrt{N_{SC}} \sqrt{F_{TDC}}$$

$$\sqrt{F_{beam}} = \begin{cases} 0.082 \text{ V/m} & dataset \ \#1 \\ 0.087 \text{ V/m} & dataset \ \#2 \end{cases} \quad (7)$$

It is interesting also to note that the best estimate of $\bar{E}_{5G}^{max}$ is only slightly higher than the maximum field value measured using Channel Power measurements, reported in [22], equal to 0.07 V/m.

C. UNCERTAINTY BUDGET

The uncertainty budget is reported in Table 3 [32]. In the following a short explanation on how the estimation of some contributions has been evaluated is reported. When possible,

TABLE 2. Mismatch uncertainty evaluation of the cable.

	Symbol	Value in dB x_{dB}
Coaxial cable attenuation	α	-3.2 dB
Antenna reflection coefficient	$\|\Gamma_{ant}\|$	-17.5 dB
Downconverter input reflection coefficient	$\|\Gamma_{dwn}\|$	-7.8 dB
$20 \log_{10} (1 + \alpha \|\Gamma_{ant}\| \|\Gamma_{dwc}\|)$	M	0.22 dB
mismatch uncertainty	$M/\sqrt{2}$	0.16

the information provided by vendors was used, in particular for the scanner [27], the downconverter [33] and the antenna [31]. The other uncertainty sources were considered as follows.

1) COAXIAL CABLE
Information on the cable attenuation was provided by the vendor.

The presence of the coaxial cable gives a further contribution to the uncertainty budget due to the presence of multiple reflections between the two terminations of the cable. This contribution is called 'cable mismatch uncertainty' in the uncertainty budget. Due to the random value of the phase in multiple reflections process, the output voltage amplitude ranges in:

$$M = 20 \log_{10} \left(\|1 \pm \alpha^2 \|\Gamma_{ant}\| \|\Gamma_{dwc}\| \right) \quad (8)$$

wherein α is the attenuation of the cable (provided by the vendor), $\|\Gamma_{ant}\|$ is the reflection coefficient of the antenna [31] and $\|\Gamma_{dwc}\|$ is the reflection coefficient at the input of the downconverter. The mismatch uncertainty has a U shape, and the standard uncertainty is obtained by dividing M by $\sqrt{2}$.

The value of the reflection coefficient at the input of the downconverter is indicated in [33] in terms of VSWR (VSWR ≤ 2.4). Therefore the reflection coefficient is

$$\|\Gamma_{dwc}\| = \frac{VSWR - 1}{VSWR + 1} = 0.41 \quad (9)$$

The quantities involved in the mismatch uncertainty of the coaxial cable are reported in Table 2.

2) gNB ANTENNA-F_{beam}
As discussed in section IV.A, supposing that the set of beams used to cover the sector overlap at 3 dB, F_{beam} value ranges from 9 to 12 dB with rectangular distribution.

3) INCIDENT FIELD FADING
The standard deviation was discussed in Section III.C, and the values are summarized in Table 1 for both data sets. The standard deviation of the mean is obtained dividing by the square root of the number of samples, giving 0.19 dB and 0.21 dB respectively.

4) EXPANSION FACTOR
Since in MPE we are interested in an upperbound of the field, we consider a one tail test of the Gaussian distribution,

TABLE 3. Uncertainty budget (dataset #1).

Component	Influence factor	Type of unc.	Specific Unc.	Distrib.	Factor	Standard Uncertanty
Scanner (device 1)	Level measurement uncertainty	B	1.5 dB	Normal	2	0.75 dB
Downconverter (device 3)	Level measurement	B	1.5 dB	Normal	2	0.75 dB
Cable (device 4)	mismatch uncertainty	B	0.22 dB	U-shape	$\sqrt{2}$	0.16 dB
Cable (device 4)	attenuation	B	0.2 dB	uniform	$\sqrt{3}$	0.12 dB
Probe antenna (device 5)	Gain	B	0.8 dB	uniform	$\sqrt{3}$	0.46 dB
Probe antenna (device 5)	Azimuth ripple	B	1 dB	uniform	$\sqrt{3}$	0.58 dB
gNB Antenna	F_{beam}	B	1.5 dB	uniform	$\sqrt{3}$	0.87 dB
Incident Field	Fading	A		Normal		0.19 dB
Combined standard uncertainty						1.59 dB
Expansion factor (one tail)						2.33
Expanded one tail uncertainty						3.70 dB
Expanded one tail uncertainty in natural value						1.53

The Table shows the uncertainty budget for dataset #1; in the uncertainty budget of dataset #2 the standard uncertainty of the incident field is 0.21 dB; however the combined standard uncertainty does not change; consequently, apart form the value of the standard uncertainty of the incident field, all the values are valid also for the dataset #2.

obtaining an expansion factor (right tail) of 2.33 and an expanded right tail uncertainty with 99% of probability equal to 3.68 dB.

Accordingly the average field level is

$$E_{5G}^{max} \leq \bar{E}_{5G}^{max} \, 1.53 =$$
$$\begin{cases} = 0.13 \ \text{V/m } dataset \ \#1 \\ = 0.13 \ \text{V/m } dataset \ \#2 \end{cases} \qquad (10)$$

with 0.99 probability.[3]

As a last observation, it must be noted that the result of the MPE is a strong upperbound that supposes that all the resources of the communication system are used by a single user placed in the measurement point. Consequently, the MPE value must be reduced by a correction factor, as recalled in the Introduction, in order to have a realistic value of the field level. This corrected value can be compared to the limits imposed by the legislation. However, the results obtained in this work show that the field level is well below both the Italian legislation (40 V/m) and the ICNIRP reference levels without applying any corrective factor.

V. CONCLUSION

In this paper the MPE methodology is applied to a FR2 signal. The results show that $E_{5G}^{max} \leq 0.13$ V/m with a probability of 99%. This rather low level of field is not completely unexpected, considering that the current state of technology poses significant limits on the generators working in FR2.

Even if the procedure has been developed in the framework of a research project, it is suitable for automatic implementation, including the uncertainty budget estimation. During the measurement only one base station station was active in FR2. However, the measurement equipment is fully able to collect data on all the gNBs eventually present in the measurement site.

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[3]Since the probe antenna is vertically polarized, it is understood that this is the MPE solution for the vertical component of the electric field; evaluation of the horizontal component would require the rotation of the probe.

The analysis of the uncertainty budget also shows the critical points of the procedure. In particular, F_{beam} estimation represents the most challenging point. The absence of detailed information on traffic and broadcast patterns and on the uncertainty of maximum value of the gain of broadcast and traffic beams forces toward some educated guesses on the pattern. As a consequence, the largest single contribution to the uncertainty budget turns out to be related to F_{beam} term. This problem, discussed also in [12] and [14] pushes toward the use of techniques able to measure the actual F_{beam} value in the measurement session to reduce the uncertainty related to this factor.

It is also worth noting that a further important contribution to the uncertainty budget is related to the probe antenna. In fact, antennas specifically designed for accurate field level measurements in FR2 are not yet on the market and the available antennas often do not pay the required attention to uncertainty evaluation, providing uncertainty ranges wider than necessary. The development of probes specifically designed for measurement in the FR2 band would allow a significant reduction in measurement uncertainty.

A further interesting result of this paper regards the log-normal distribution of the measured quantity. The knowledge of the sampling distribution allows to apply the theory of small samples, offering a rigorous mathematical framework to reduce the number of measurements.

Finally, it is understood that the approach followed in the paper, and based on a rigorous estimation of the uncertainty budget, also allows a rigorous method to compare the different implementations of the MPE technique proposed in literature. Comparison of the specific measurement set-up used in the paper with different MPE technical solutions, based on scalar or vector spectrum analyzers, is out of the scope of this paper, but will be considered in future contributions.

company) to provide the experimental data and for their invaluable help in analyzing the measured data.

REFERENCES

[1] International Commission on Non-Ionizing Radiation Protection, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, pp. 483–524, May 2020.

[2] *Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*, document IEC 62232:2017, 2017.

[3] P. Baracca, A. Weber, T. Wild, and C. Grangeat, "A statistical approach for RF exposure compliance boundary assessment in massive MIMO systems," in *Proc. 22nd Int. ITG Workshop Smart Antennas*, 2018, pp. 1–6.

[4] B. Thors, A. Furuskär, D. Colombi, and C. Törnevik, "Time-averaged realistic maximum power levels for the assessment of radio frequency exposure for 5G radio base stations using massive MIMO," *IEEE Access*, vol. 5, pp. 19711–19719, 2017.

[5] D. Pinchera, M. D. Migliore, and F. Schettino, "Compliance boundaries in 5G communication systems: A statistical approach," *IEEE Access*, vol. 1, pp. 620–628, 2020.

[6] D. Colombi, P. Joshi, B. Xu, F. Ghasemifard, V. Narasaraju, and C. Törnevik, "Analysis of the actual power and EMF exposure from base stations in a commercial 5G network," *Appl. Sci.*, vol. 10, no. 15, p. 5280, Jul. 2020.

[7] M. D. Migliore and F. Schettino, "Power reduction estimation of 5G active antenna systems for human exposure assessment in realistic scenarios," *IEEE Access*, vol. 8, pp. 220095–220107, 2020.

[8] A. Schiavoni, S. Bastonero, R. Lanzo, and R. Scotti, "Methodology for electromagnetic field exposure assessment of 5G massive MIMO antennas accounting for spatial variability of radiated power," *IEEE Access*, vol. 10, pp. 70572–70580, 2022.

[9] R. Pawlak, P. Krawiec, and J. Z. Żurek, "On measuring electromagnetic fields in 5G technology," *IEEE Access*, vol. 7, pp. 29826–29835, 2019.

[10] S. Aerts, L. Verloock, M. Van Den Bossche, D. Colombi, L. Martens, C. Törnevik, and W. Joseph, "In-situ measurement methodology for the assessment of 5G NR massive MIMO base station exposure at sub-6 GHz frequencies," *IEEE Access*, vol. 7, pp. 184658–184667, 2019.

[11] H. Keller, "On the assessment of human exposure to electromagnetic fields transmitted by 5G NR base stations," *Health Phys.*, vol. 117, no. 5, pp. 541–545, 2019.

[12] S. Adda, T. Aureli, S. D'Elia, D. Franci, E. Grillo, M. D. Migliore, S. Pavoncello, F. Schettino, and R. Suman, "A theoretical and experimental investigation on the measurement of the electromagnetic field level radiated by 5G base stations," *IEEE Access*, vol. 8, pp. 101448–101463, 2020.

[13] S. Aerts, K. Deprez, D. Colombi, M. Van den Bossche, L. Verloock, L. Martens, C. Törnevik, and W. Joseph, "*In situ* assessment of 5G NR massive MIMO base station exposure in a commercial network in bern, Switzerland," *Appl. Sci.*, vol. 11, no. 8, p. 3592, Apr. 2021.

[14] M. D. Migliore, D. Franci, S. Pavoncello, E. Grillo, T. Aureli, S. Adda, R. Suman, S. D'Elia, and F. Schettino, "A new paradigm in 5G maximum power extrapolation for human exposure assessment: Forcing gNB traffic toward the measurement equipment," *IEEE Access*, vol. 9, pp. 101946–101958, 2021.

[15] T. Kopacz, S. Schiesl, A.-M. Schiffarth, and D. Heberling, "Effective SSB beam radiation pattern for RF-EMF maximum exposure assessment to 5G base stations using massive MIMO antennas," in *Proc. 15th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2021, pp. 1–5.

[16] A.-K. Lee, S.-B. Jeon, and H.-D. Choi, "EMF levels in 5G new radio environment in Seoul, Korea," *IEEE Access*, vol. 9, pp. 19716–19722, 2021.

[17] T. Jiang and A. K. Skrivervik, "Assessment of the electromagnetic field exposure due to 5G base stations using a monte-carlo method: Initial results," in *Proc. 15th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2021, pp. 1–4.

[18] C. Bornkessel, T. Kopacz, A.-M. Schiffarth, D. Heberling, and M. A. Hein, "Determination of instantaneous and maximal human exposure to 5G massive-MIMO base stations," in *Proc. 15th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2021, pp. 1–5.

[19] D. Franci, S. Coltellacci, E. Grillo, S. Pavoncello, T. Aureli, R. Cintoli, and M. D. Migliore, "An experimental investigation on the impact of duplexing and beamforming techniques in field measurements of 5G signals," *Electronics*, vol. 9, no. 2, p. 223, Jan. 2020.

[20] S. Liu, T. Onishi, M. Taki, M. Ikuyo, K. Tobita, S. Watanabe, and Y. Suzuki, "E-field strength measurements of a 5G base station in 28 GHz band for EMF exposure assessment," in *Proc. IEEE USNC-URSI Radio Sci. Meeting Joint AP-S Symp.)*, Dec. 2021, pp. 49–50.

[21] S. Q. Wali, A. Sali, J. K. Allami, and A. F. Osman, "RF-EMF exposure measurement for 5G over mm-wave base station with MIMO antenna," *IEEE Access*, vol. 10, pp. 9048–9058, 2022.

[22] L. Chiaraviglio, C. Lodovisi, D. Franci, S. Pavoncello, E. Merli, T. Aureli, N. Blefari-Melazzi, M. D. Migliore, and M.-S. Alouini, "EMF exposure in 5G standalone mm-wave deployments: What is the impact of downlink traffic?" *IEEE Open J. Commun. Soc.*, vol. 3, pp. 1445–1465, 2022.

[23] C. Hausl, J. Emmert, M. Mielke, B. Mehlhorn, and C. Rowell, "Mobile network testing of 5G NR FR1 and FR2 networks: Challenges and solutions," in *Proc. 16th Eur. Conf. Antennas Propag. (EuCAP)*, 2022, pp. 1–5.

[24] *Radio Transmission and Reception (Release 15)*, document TS 38.104, Version 15.5.0, 3GPP, Technical Specification Group Radio Access Network; NR, May 2019.

[25] C. R. Paul, *Introduction to Electromagnetic Compatibility*, vol. 184. Hoboken, NJ, USA: Wiley, 2006.

[26] N. Alliance, "Recommendation on base station active antenna system standards," Tech. Rep., 2021. [Online]. Available: https://www.ngmn.org/publications

[27] Rohde and Schwarz. (2022). *TSMA6B Autonomous Mobile Network Scanner—Product Brochure*. [Online]. Available: https://www.rohde-schwarz.com/it/brochure-scheda-tecnica/tsmx/

[28] G. Betta, D. Capriglione, G. Cerro, G. Miele, and M. S. D'Amata, "Human exposure to 4G LTE systems: Enhancing the reliability of EMF extrapolation techniques based on spectrum analyzer measurements," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–13, 2021.

[29] G. Betta, D. Capriglione, G. Cerro, G. Miele, M. D. Migliore, and D. Suka, "5G DSS communications: Pilot signals' variability analysis from measurements on the field," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (IMTC)*, May 2022, pp. 1–6.

[30] H. L. Bertoni, *Radio Propagation for Modern Wireless Systems*. London, U.K.: Pearson Education, 1999.

[31] (2022). *Steatite Q Par Antennas QOM-SL-26-40-K-SG-R—Product Brochure*. [Online]. Available: https://www.steatite-antennas.co.uk/wp-content/uploads/2017/09/QOM-SL-26-40-K-SG-R.pdf

[32] E. Bronaugh and D. Heirman, "Estimating measurement uncertainty—A brief introduction to the subject," in *Proc. EMC*, 2004, pp. 1093–1098.

[33] Rohde and Schwarz. (2022). *TSME6 Ultracompact Drive Test Scanner—Product Brochure*. [Online]. Available: https://www.rohde-schwarz.com/it/brochure-scheda-tecnica/tsmx/

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