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Human exposure to EMF from 5G base stations: analysis, evaluation and comparison of different assessment methods

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ABSTRACT

5G networks deployment poses new challenges when evaluating human exposure to electromagnetic fields. Fast variation of the user load and beamforming techniques may cause large fluctuations of 5G base stations field level. They may be underestimated, resulting in compliance of base stations not fitting the requirements. Apparently, broadband field meters would not be adequate for measuring such environments. However, we analyze the feasibility of confidently using broadband field meters and compare their performance with alternative equipment. Measurements based on the synchronization signals power level, using spectrum analyzers or drive test scanners, may be valid, if gain differences between the signaling and data radiation patterns are characterized. These methods lead to good results but require more time and knowledge. Nevertheless, using broadband field meters is still possible if the measurement results are corrected considering the base station load. Under specific conditions, explained here, fast assessment of 5G compliance could be provided.

1. Introduction

The increasing demand of new services and applications in mobile communications during the last years has resulted in the evolution of mobile communication standards, with new releases and generations leading to the current fifth generation (5G) [1] and beyond. 5G is offering more capacity and flexibility, supporting new applications, as for example massive internet of things (IoT).

This flexibility to optimize the use of the resources, joined to higher signal bandwidths, increases the variability of the base station load compared with previous generations. The roll-out of 5G networks necessarily implies the deployment of new base station equipment, including new radiating systems. These systems may be provided with massive multiple-input multiple-output (M−MIMO) capabilities, where up to a hundred antenna elements are used for beamforming. Thus, the assessment of the associated electromagnetic field (EMF) in their coverage areas becomes more complex.

Despite this additional complexity, the EMF level generated by such antennas must comply with ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines [2] and the related current legislation on human exposure, at the national or international level ([3–6]). The basic restrictions to human exposure to EM fields, for general public, established by the mentioned guidelines are summarized in Table 1.

These basic restrictions for the specific absorption rate (SAR) of electromagnetic energy deposition in human tissues, which are not easy to measure, have been translated into quantities that allow a straightforward assessment, known as reference levels respectively field strengths in air or power density [2]. They provide a protection equivalent to basic restrictions considering the worst-case conditions. Table 2 contains these reference levels as recommended by [2].

International and national regulations in Europe are commonly following the ICNIRP guidelines [2], even though the refreshing rhythm of laws are not the same of scientific research, and thus some of them are still applying previous versions of those guidelines [3–6]. Some countries adopted more restrictive EMF constraints; but this decision often penalties the user equipment and, thus, the perceived quality of service [7]. Anyway, there is a strong interest in assessing properly the human exposure to the EMFs associated to 5G base stations, as they will have a relevant impact in the electromagnetic environment the following years.

Usually, the target parameter to be measured is the electric field strength (as reference levels are defined over it). This means that the main units in the measurements should be V/m (or, alternatively, dBuV/m). Reference levels are also defined in terms of magnetic field strength

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Table 1
Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for averaging intervals of 6 min [2].

Frequency range	Local Head/Torso SAR (W kg^{-1})	Local Limb SAR (W kg^{-1})	Local S_{ab} (W m^{-2})
100 kHz to 6 GHz	2	4	NA
>6 to 300 GHz	NA	NA	20

Table 2
Reference levels for local exposure, averaged over 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values) [2].

Frequency range	Incident E-field strength E_{inc} (V/m)	Incident H-field strength H_{inc} (A/m)	Incident power density S_{inc} (W m^{-2})
0.1 – 30 MHz	671 / $f_M^{0.7}$	4.9 / f_M	NA
>30 – 400 MHz	62	0.163	10
>400 – 2000 MHz	4.72 $f_M^{0.43}$	0.0123 $f_M^{0.43}$	0.058 $f_M^{0.86}$
>2 – 6 GHz	NA	NA	40
>6 – 300 GHz	NA	NA	55 / $f_G^{0.177}$
300 GHz	NA	NA	20

*Being fM and fG the frequency in MHz and GHz, respectively.

and in power density. Of course, magnetic and electric field strengths magnitudes are directly related when the measurements are gathered at far field conditions, in which case is enough to check only one of these magnitudes.

A variety of studies [8–13] have demonstrated significant temporal fluctuations of the exposure level, by monitoring the electromagnetic field during long periods of time (one day, one week or even longer) in preceding cellular communication generations. Such uncontrolled variations add an important component of uncertainty in the measurement that is expected to be more pronounced for the latest mobile communication generations. Thus, the expected larger variations of the 5G base station load, due to the load management policy of this new generation, would lead to increased uncertainty in EMF field level measurements. One of the objectives of this work is to explore the magnitude of the problem by analyzing this larger measurement uncertainty within 5G environments. Uncertainty assessment is omitted in many occasions when presenting measured data, even though the gathered data are only an approximation of the values of the physical magnitude which needs to be completed by some indications on its reliability [14]. The interest of such uncertainty analysis is supported by its consideration in the recent publication of supplement 16 to ITU-T Series K [15], which reinforces the particular importance of providing uncertainty estimates when determining 5G compliance with exposure limits. This analysis should consider both the measurement equipment limitations and other sources as the applied postprocessing, the mechanical constraints and the own definition of the physical parameters [14].

When talking about measuring EMF levels, field strength meters with broadband probes have been the equipment most widely used. They allow to measure the total field value of all signals within the frequency range of the probe without any frequency-related information [16,17]. With this equipment, overall field levels in the environment can be acquired and compared to the exposure limits [18]. In short, broadband field instruments provided a fast EMF level assessment to assure compliance with regulation on human exposure in most of the environments, at a reasonable cost. The increased complexity of 5G signals may change the situation, and therefore the suitability of this kind of instruments to assess the exposure levels in presence of 5G signals has to be determined. During the last years, the research efforts have focused on measuring the field level with alternative equipment: frequency selective equipment, like spectrum analyzers (SA), or drive test scanners (DTS) that demodulate the received signal to estimate several quality parameters [19–24]. In these alternative methods, the power of the received 5G signal is partially measured, instead of the total field level in a broad frequency band. The synchronization signal block (SSB) power seems to be one of the more adequate signals to be measured, as it is periodically transmitted at a constant power, independently of the base station load (also in absence of user data traffic [24]). Then, measurement results can be extrapolated to estimate the total 5G signal power at full load, which would correspond to the worst-case of EMF exposure. The extrapolation is not easy due to the signal power differences, and also to the difference in the gain of the antenna patterns used to transmit the SSB and the user data, as remarked in [25].

Along this work, we give advice on how to approach the worst exposure case with such broadband field instruments and we also compare the results obtained when assessing the EMF of an actual 5G base station with other methodologies and equipment. On a first attempt, the assessment with a broadband field meter is done without control on the base load, as it is usually done in EMF assessment. Then, the measurement is repeated while a 5G user terminal is employed to download a heavy file, so the station is loaded at least with some data rate. The induced data rate is registered for subsequent analysis of the measurement results. Measurements of the SSB power are also conducted using an SA and a DTS in parallel to those done with the broadband field meter. Finally, the values from the different methods are compared to extract some conclusions, providing the pros and cons of each solution, and analyzing their suitability. As a consequence, we can enunciate the conditions under which the simplest methodology, i.e. the broadband field meter, can be used for these purposes. This result would provide scientific support to the technicians assessing human exposure to EMF around 5G stations for using broadband instruments.

Then, three are the contributions of this paper. Providing measured data within an actual 5G base station environment, gathered by three different procedures applied simultaneously at the same time and at the same locations is the first one. Comparing the results provided by these three procedures, taking into account their own uncertainties is the second one, which was never done before, to the best authors' knowledge. And finally, the main contribution, derived from the comparison of the three measurement strategies: demonstrating that a broadband field meter can be used for assessing human exposure to EMF in the vicinity of 5G base stations which produce fields with extreme fluctuations as a consequence of the system load and beamforming configuration variation.

After this introduction section, this article is organized as follows. Section 2 focuses on 5G physical layers to describe how the information is allocated, identifying which part is fixed and which depends on user load, as a theoretical support to the experiments performed during this research. Section 3 presents a brief analysis of the uncertainty in the field level assessment due to uncontrolled variations of the 5G base station load, which are the main sources of error in this human exposure assessment procedure and, thus, the element to be understood and controlled for analyzing the different approaches to the problem. In section 4, the different methods and equipment used to assess the EMF generated by an actual 5G base station are summarized, describing the main configuration parameters as a previous step to the measurement campaign. Then, measurement results are provided in section 5 and discussed in section 6, which allows a deep comparison among the three considered methods. Finally, we draw some conclusions in section 7, with special care in the conditions for which the different methodologies are valid and safe for assessing the human exposure to EMF around 5G base stations.

2. 5G physical layer

The 5G wireless access, also known as 5G new radio (5G NR), has been designed to address the major challenges 5G systems will have to deal with: a massive traffic volume, a huge number of devices and a wide range of applications, including the enhanced mobile broadband services (eMBB), the ultra-high reliable and low latency communications

(URLLC) and the massive machine-type communications (MMTC). In this design process, several performance parameters were considered as: spectral efficiency, peak-to-average power ratio (PAPR), robustness against time and frequency fading, flexibility and scalability, etc.

5G NR supports different OFDM (orthogonal frequency division multiplexing) modulation numerologies [26]. Each of them is defined by its sub-carrier spacing (SCS) and its cyclic prefix (CP) overhead. SCS of $15 \cdot 2^n$ kHz is used, where n is a positive integer, and with a CP length occupying 7 % of the symbol duration.

The time–frequency resources are organized as follows. One subcarrier in one OFDM symbol constitutes a resource element (RE). A resource block (RB) is defined as 12 contiguous subcarriers in the frequency domain. The bandwidth occupied by each RB depends on the numerology. In the time domain, one frame consists of 10 sub-frames of 1 ms each. Each sub-frame contains one or more adjacent slots (depending on the numerology) and each slot is made of 14 symbols. The NR frame structure supports both time division duplexing (TDD) and frequency division duplexing (FDD) transmissions. TDD is more suitable for unpaired spectrum allocations. The uplink and downlink allocations in TDD can change dynamically to adapt to rapid traffic variations.

In order to cope with the strong signal attenuation at millimeter-wave frequencies, the use of directional links has been considered in 5G. The directional beams are achieved through multiple antenna systems and beamforming. 5G NR functions support M−MIMO antenna processing and beamforming, both for user data transmission and for initial access and broadcast signals.

For the purposes of this paper, special attention will be paid to SSB (Synchronization Signal Block). This block (see Fig. 1) is made up of 240 subcarriers (20 RB) and 4 OFDM symbols, and it allocates the following channels and signals:

- Physical broadcast channel (PBCH). It carries the system information to enable the user terminal to access the 5G network and uses QPSK modulation.
- Primary synchronization signal (PSS). It is generated by using a BPSK modulated m-sequence of length 127.
- Secondary synchronization signal (SSS). It is generated by using BPSK modulated Gold sequence of length 127.

The center frequency of the SSB is not fixed and, therefore, it depends on the base station. It is transmitted periodically with a period ranging from 5 ms to 160 ms, depending also on the base station configuration. SSB may be transmitted by a single beam or sequentially by up to eight adjacent directional beams, sweeping the coverage area. The actual base station used for this research transmits the SSB with a periodicity of 20 ms by just one single beam. This information will determine how many times we can record the SSB in each sweep done with the SA. As it has been tested that SSB power level shows certain variability in complex scenarios [27], averaging several SSB samples would improve any extrapolation performed using this power amplitude.

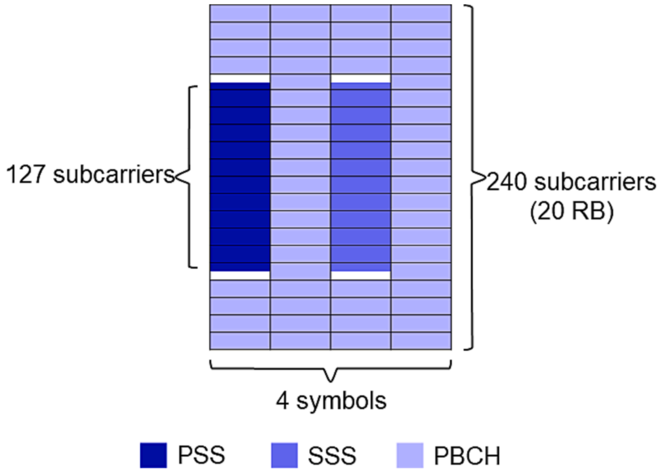


Fig. 1. SSB structure.

3. Theoretical uncertainty derived from user load fluctuations

As 5G signals have increased bandwidths in comparison with previous generations, higher variations of the field level with the load are also expected. To assure full compliance of a transmitter with the legislation on human exposure, measurements should be performed in the worst-case scenario, i.e. with the base station working at full load and transmitting the maximum authorized power towards the measurement equipment. During measurements, in general, the researcher does not control the base station load. Besides, the antenna beam pointing, as a result of beamforming processes, is also out of researcher's control. Both facts generate additional uncertainty related to the user load.

The quantity to be determined is the maximum RMS electric field strength generated by the transmitter, E_{max}. In practice, we are measuring E_i, the RMS field strength for a specific percentage of load i. Thus, the error when trying to assess the worst-case exposure without knowledge about the load, $\Delta load_i$, can be defined as the logarithmic ratio of these two quantities:

$$\Delta load_i = 10\log_{10}\frac{E_{max}^2}{E_i^2} \tag{1}$$

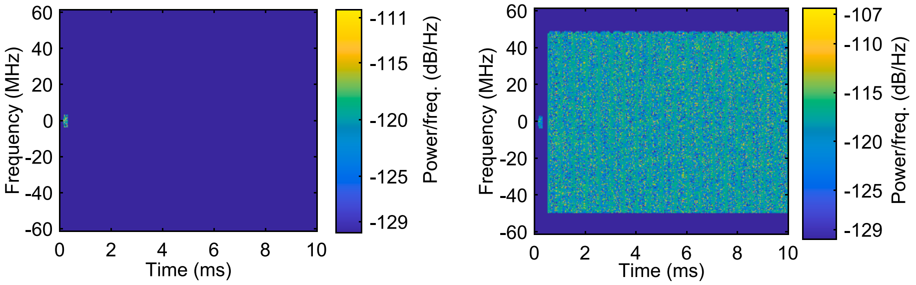
with this definition, the maximum error carried out when evaluating the worst-case exposure assessment, $\Delta load_{max}$, would be determined by the field level ratio from the maximum to the minimum load.

In 5G, the only signal always transmitted independently of the user load is the SSB. If we have a 100 MHz bandwidth signal with a 30 kHz SCS and an FDD scheme, our available resources will be 3,300 subcarriers (100 MHz/30 kHz) in frequency and 280 symbols per frame in time (20 slots per frame and 14 symbols per slot). Thus, the SSB, when transmitted every 10 ms, will occupy a 0.1 % of the resources. In this case the difference between zero load (only SSB) and full load will be around 30 dB. Values can slightly vary depending on the periodicity of SSB transmission (between 5 ms and 160 ms). If the transmission is TDD, with the uplink occupying one subframe, the difference would be 29.2 dB.

Theoretical calculation of the $\Delta load_{max}$ can roughly be done as shown below. However, the estimation of the error for other loads is not that easy. Thus, to evaluate the error $\Delta load_i$ for different loads, a double approach including simulations and measurements has been chosen. The first step in the simulation procedure was to generate a set of waveforms by using Matlab® software. The configuration was as follows:

- Single-antenna transmission
- 64-QAM modulation
- 100 MHz channel bandwidths
- 30 kHz SCS
- Randomly generated input user data stream
- FDD mode. Although there are many TDD deployments, FDD was chosen as it leads to the worst-case.
- Load between 0 % and 100 % in steps of 1 %.

The spectrogram of waveforms for 0 % and 100 % of user load are shown in Fig. 2, in which the scale represents the signal strength in dB/Hz (power per unit of bandwidth). Here the numerical values are not relevant, as the objective is to graphically show the differences in spectrum occupancy between two load situations. In this case, the SSB block is centered in the band, but in a real case it could be at any position in the frequency band. As we can also notice from the spectrograms, the first slot is only occupied by the SSB. In a real transmission, and



(a) (b)

Fig. 2. Spectrogram of 5G downlink waveforms. (a) 0 % of load. (b) 100 % of load. Note that SSB is the signal that appears at the first time slot and center frequency at both (a) and (b) plots (left side of the plots).

depending on the periodicity, such slot could also carry user data. Taking this into account, the theoretical 30 dB for the maximum exposure error calculated above would be reduced to 29.6 dB: the difference comes from the exclusive use of the first slot for signaling in our simulations.

Once we have the waveforms, a measurement event with an ideal probe has been simulated, selecting as many samples from the generated waveforms as in a real case (samples taken every 1 s over a 6-minute period as established in ICNIRP guidelines [2]). By an ideal probe we mean a probe able to measure the true RMS value of the signal. Results of the simulation of a field measurement are shown in a black dotted line in Fig. 3, where we plot $\Delta load_i$ as a function of the load, i. The maximum error in the worst-case exposure level is 29.46 dB, which is in agreement with the theoretical computation previously presented. The increment (in dB) is sharpest in the lowest percentages of occupation. When the load is around the 4 %, the difference with the full load level is reduced from 29.46 dB to 14.13 dB.

Finally, results from the simulations are compared with measurements done inside an anechoic chamber. The signals corresponding to different loads are transmitted with an antenna connected to an RF signal generator. The frequency was set to 3.500 MHz, corresponding to band n78, in which the current 5G deployments in Europe are being operated. On the receiver side, the wideband field probe WPF8 from Wavecontrol, connected to the SMP2 reader unit was used.

For the measurements, loads from 0 % to 5 %, in steps of 1 %, and from 10 % to 100 %, with a 10 % step, have been considered. Smaller steps were selected for the lowest percentages of load as the changes in exposure error resulted to be steeper in the simulations.

Fig. 4 depicts the spectrums of the signals with 10 %, 50 %, and 100 % load at the generator output. The RMS value of the electric field for each transmitted signal was computed after measuring over 6 min. The measured RMS field strength for each load normalized to the maximum RMS value is plotted also in Fig. 3 (red continuous line) together with the simulated results. The measurement results agree with the simulations, exhibiting a maximum error around 29.1 dB. Here we have also to consider the uncertainties associated to the probe and to the environment, that for our particular case (single frequency in a controlled environment) is estimated to be 2.39 dB. The uncertainty associated to the user load clearly represents the dominant contribution.

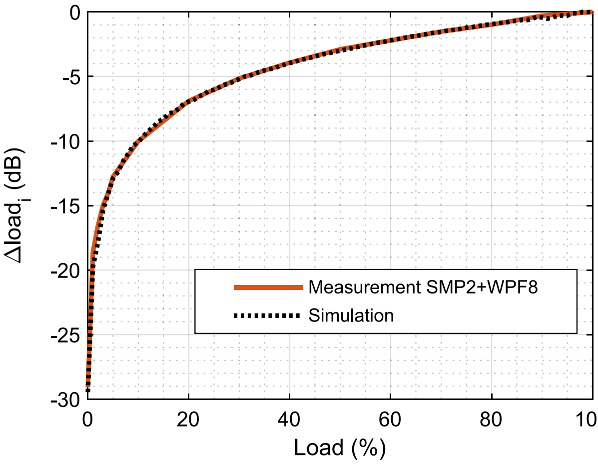


Fig. 3. Logarithmic ratio of the maximum RMS field strength to the RMS field for each user load, $\Delta load_i$, obtained in simulations (black dotted line) and in measurements (red solid line).

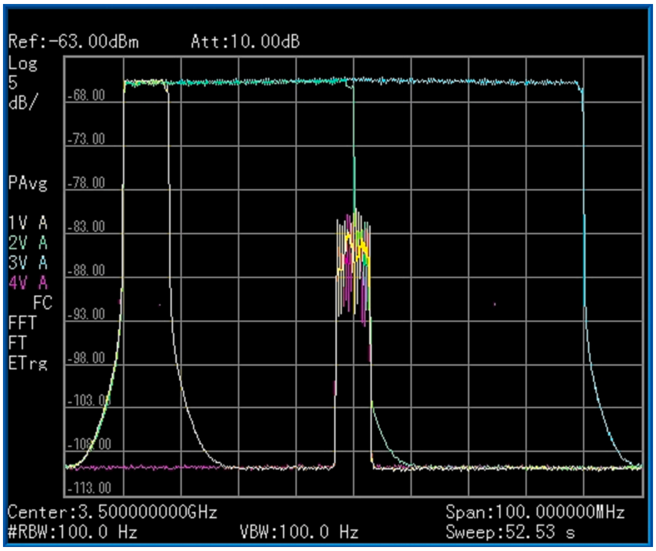


Fig.4. Spectrum of 5G signals with 0 % (purple), 10 % (yellow), 50 % (green), and 100 % (blue) load.

4. Measurement setup and environment

The experimental part of the research consists of a measurement campaign to assess the human exposure to EMF in the surroundings of an active 5G base station. For conducting those measurements, we used three different kinds of equipment: a broadband field meter with isotropic probe, an SA and a DTS, placed at the same spots and gathering data at the same time and, thus, in similar load and antenna beam pointing conditions. Prior to the measurement campaign itself, in this section, we describe the particularities of the measurement and configuration for each equipment. The measurement procedures are like those described in the norm IEC 62232:2022 [18].

Besides, the description of the measurement environment is included at the end of this section, completing the necessary background for performing such a comparison.

4.1. Broadband field meter

The Wavecontrol WPF8 field probe with the SMP2 reader is used to gather the RMS value of the E-field level in a frequency range from 100 kHz to 8 GHz. This is a three-axis isotropic probe for E-field with broadband diode detectors. This type of detectors exhibits a high noise figure that results in low sensitivity and contributes to a high uncertainty of the measurements. Besides, the probe is unable to resolve the power as a function of frequency. On the other hand, these probes neither require frequency tuning, nor antenna orientation, making the measurement process easy and quick. As stated in the safety recommendation of the ICNIRP [2], the measurement of the EMF level with a broadband probe should be 6 min long, at a sampling rate of 1 sample/s, to get an accurate estimate of the exposure. However, it is unlikely that the base station would radiate at its maximum power during this period, which is a source of uncertainty. Another source is the dynamic behavior of the base station radiation pattern, due to the beamforming system, and the potential positioning of the probe off-center of the beam.

A possible approach to assess the worst-case of human exposure, that is the one taken in this research, is to conduct the 6-minute measurement while a 5G user terminal is employed to download a heavy file, from a position close to the probe. Thus, we guarantee both a certain amount of load to the base station during the measurement period, and the pointing of (or at least, one of) the antenna beam to the probe. The download data rate achieved is recorded by an application at the user terminal, and then used to extrapolate the measurement result to the full load case. We take advantage of the iPerf tool [28] to generate data traffic in the download link. However, as the iPerf tool does not guarantee the same downlink traffic at each point, different points endured a different amount of load. Extrapolation to full load case is done as:

$$E_{max} = E_{measured}\sqrt{\frac{maximum\_rate}{measurement\_rate}} \tag{2}$$

where *measurement_rate* is the downlink rate produced with the iPerf tool, and *maximum_rate* is the actual maximum capacity of the base station. At the time we have performed the measurements, the transmissioen was limited to 400 Mbits/s in the considered base station, according to the network operator information. In case the actual maximum data rate is unknown, the correction should be made using the maximum value provided by the standard.

The field reader used for measuring stores the maximum peak value in addition to the RMS value during the 6-minute measurement period. These values will be compared to RMS extrapolated ones and to the maximum values measured with the SA in the next section.

4.2. Spectrum analyzer

4.2.1. Basics

SAs are general purpose measurement equipment able to measure the power of the signal at its port as a function of frequency. They are mostly made using a heterodyne receiver with a voltage controlled local oscillator to make a frequency sweep from an initial frequency to a final frequency, both specified by the user. The measurement noise depends on the intermediate frequency (IF) filter bandwidth (RBW). Modern SAs digitize the signal at the IF by using A/D converters. This results in enhanced post-processing functions of the measured spectrum. The SA can also be used to measure time variation of the power of the signal that lays within a certain bandwidth around the center frequency. This can be accomplished by setting the sweep span to zero. Then, the measurement bandwidth will be the RBW.

We have used the SA FieldFox N9913A from Keysight with an RF working frequency up to 4 GHz and 1001 measurement samples per frequency sweep, and an H300 active directional antenna from R&S. Functionalities of the SAs are evolving continuously, giving them options for signal analysis and decoding, and also massive data acquisition and storing for spectrograms generation [29,30]. However, the objective here is to analyze the viability of using simpler and more affordable instruments; therefore, such capabilities are not exploited.

4.2.2. Locating the signaling

Before performing the power measurement of the SSB, its center frequency must be determined. According to 5G NR standard [26], its exact frequency location may vary from one base station to other. Fortunately, the SA can also be used for this scanning purpose.

A frequency scan is done to locate the center frequency of the SSB signal: the center frequency of the scan is set to 3.63 GHz and the span to 100 MHz around this center frequency, because 100 MHz is the largest bandwidth for FR1 5G signals. The base station used for the experiment, transmits a 5G signal with an SCS of 30 kHz, therefore, in order to differentiate the subcarriers, RBW is set to 30 kHz. The measurement time per frequency point should be longer than the length of the SSB (143 μs). To be able to resolve the SSB from user data, it is convenient to average as many samples as possible for each frequency component. The SSB is a constant-power periodic signal while those carrying user data are not, so using an RMS detector will average down the user data signals while the SSB level remains unchanged [21]. Besides, averaging mitigates the effect of the 5G pilot signals variability studied by [27]. This will help to identify the SSB. The number of samples averaged at each frequency point increases by increasing the sweep time. For this experiment, a sweep time around 120 s was used.

The center frequency of SSB was experimentally found to be around 3610.6 MHz with a span of 7.2 MHz in the base station under study, as shown in Fig. 5. As defined by the standard [31], the SSB is located at specific discrete frequency positions, known as SSREF. In the range from 3 GHz to 24.25 GHz they are given by eq. (3), with N ranging from 0 to 14756. Thus, the actual SSB frequency position of our measured 5G signal is deduced by finding the SSREF value closest to 3610.6 MHz, which is 3610.56 MHz.

$$SS_{REF} = 3000\,MHz + N \bullet 1.44\,MHz \tag{3}$$

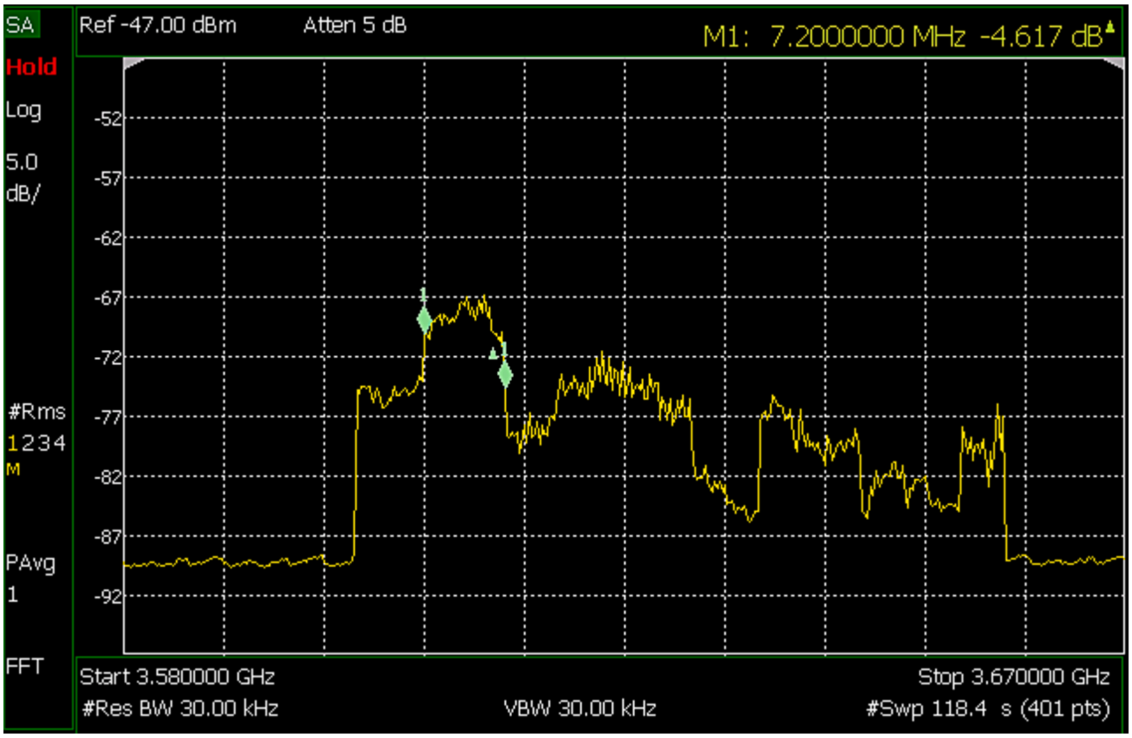
From the same measurement outcome, we can also conclude that the actual bandwidth of 5G base station was 60 MHz. This information will be relevant for extrapolating SSB measurement results.

4.2.3. Field assessment

We have used two methodologies to assess the human exposure from SA measurements, both in time domain (zero span). One of the methods is based on measuring the SSB and the other on measuring the power of the 5G signal in the RBW [18]. Both values provide a partial value of the signal power that will have to be extrapolated to obtain the full signal power. Thus, as in the case for the broadband field meter, measurements will be repeated, but inducing an increased base load.

4.2.3.1. Measuring SSB. As explained in the introduction section, current trends to assess the 5G EMF level rely on the measurement (and subsequent extrapolation) of the SSB power, or a known percentage of this power, as this value should be independent of the load. This can be done by performing several time sweeps to record the power variations within a bandwidth around the SSREF. For that, the configuration of the SA is set as follows:

- In zero-span mode.
- The central frequency is set to SSREF.
- The RBW should be the widest possible value to have an accurate average value, but narrower than 7.2 MHz. So, the SSB bandwidth is not exceeded.
- The VBW should be equal or wider than the RBW to avoid underestimation.



Ref -47.00 dBm

Atten 5 dB

M1: 7.2000000 MHz -4.617 dB

Start 3.580000 GHz

Stop 3.670000 GHz

#Res BW 30.00 kHz

VBW 30.00 kHz

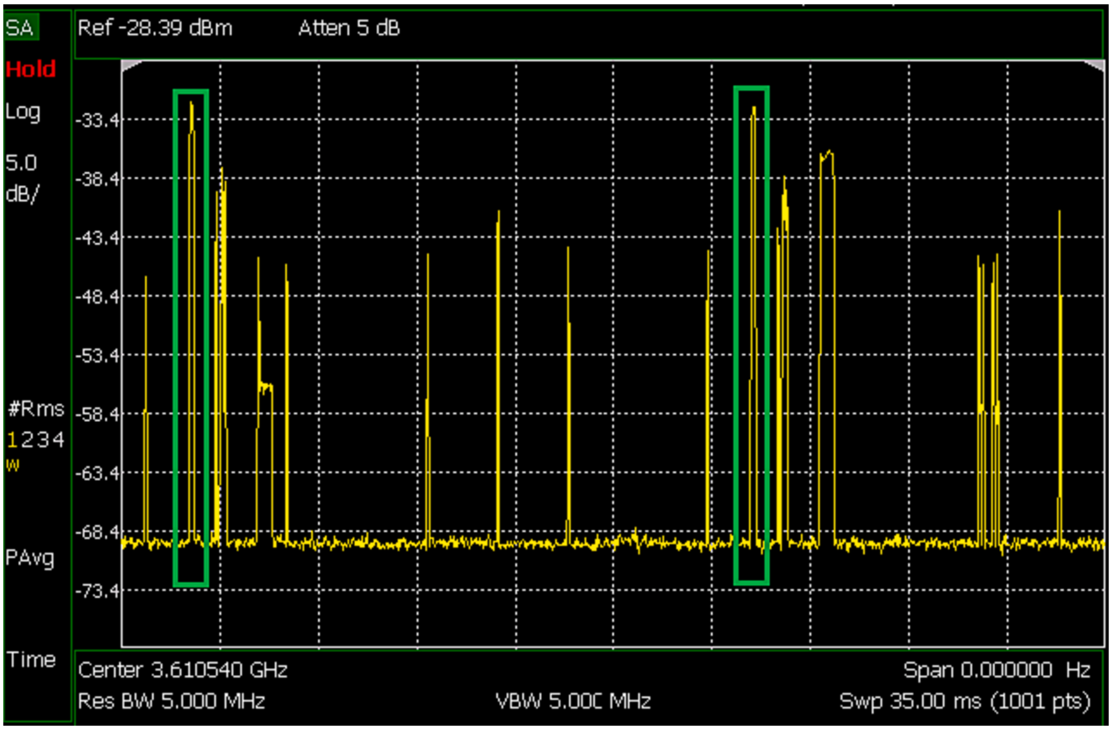
#Swp 118.4 s (401 pts)

Fig. 5. Capture of the 5G Synchronization Signal Block, with a span of 7.2 MHz (SSB is limited by the two green diamond markers which bandwidth results are at top right under M1 label).

- The sweep time must be chosen so that the measuring time per point does not exceed the length of one OFDM symbol (35.68 μs for an SCS of 30 kHz).
- Setting the type of detector to RMS is the last configuration [20].

For our measurements, we have set RBW and VBW to 5 MHz, the number of points to 1001 (both to the maximum the equipment allows) and the sweep time to 35 ms. We have chosen a sweep time large enough to get twice SSBs in a measurement trace, but short enough to improve time resolution and easily identify the SSB by visual inspection during the measurement process.

With this configuration, we have taken 10 records. As it can be seen



Ref -28.39 dBm

Atten 5 dB

Center 3.610540 GHz

Span 0.000000 Hz

Res BW 5.000 MHz

VBW 5.00C MHz

Swp 35.00 ms (1001 pts)

Fig. 6. Zero-span measurement showing a capture with two 5G Synchronization Signal Blocks (indicated by green rectangles).

in Fig. 6, user data can be sent in the same frequency bandwidth than SSB, but in different time slots. Most of the records get the SSB twice, as it is transmitted with a periodicity of 20 ms. For the measurements repeated while inducing certain load to the base, the number of time slots occupied by user data increases, as it can be verified in Fig. 7, and their power levels also increase, as a consequence of the data beam pointing toward the SA antenna. Level values extracted from these individual measurements of the SSB and user beams will be used to estimate the gain correction factors necessary to extrapolate the SA and the DTS measurements.

To estimate the total 5G field level from these measurements we proceed as follows:

- An RMS value of the SSB power within RBW, P (dBm), is calculated with the data from all the records.
- The power value, P, is converted to the electric field, E (V/m), by using the antenna factor, AF (dB/m), of the SA antenna,

$$E_{measured} = \frac{1}{\sqrt{20}} \bullet 10^{\frac{P+AF}{20}} \tag{4}$$

- As the value acquired with the SA corresponds to the power within RBW, we extrapolate it to the full signal bandwidth as follows,

$$E_{fullBW} = E_{measured} \bullet \sqrt{\frac{BW_{signal}}{RBW}} \tag{5}$$

In this case, the maximum available bandwidth of the 5G signal is 60 MHz and the SA was configured with an RBW of 5 MHz, so the correction factor to be applied is 3.46.

- The last step is the compensation of the power difference of the SSB and the user data by multiplying with the gain correction factor (k_{gain}) estimated from the measurement records, i.e. by comparing the power of the SSB and the user data. To get the last one we increase the load of the station by downloading data files, to force the data beam to point toward the SA antenna.

$$E_{corrected} = E_{fullBW} \bullet k_{gain} = E_{fullBW} \bullet \sqrt{\frac{G_{data}}{G_{SSB}}} \tag{6}$$

where G_{data} is the power from the data beam, and G_{SSB} the power from the signaling beam, in natural units, both obtained from the individual sweeps taken (see Fig. 7).

This corrected electric field ($E_{corrected}$), which is expressed in V/m, is the magnitude to be compared to the reference levels (see Table 2) [2].

4.2.3.2. Max-hold mode measurements. Frequency selective techniques [18,19], focused on measuring synchronization signals, have been proposed for human exposure assessment to LTE transmission (4G). The method consists of using SA with a configuration similar to the one in the previous subsection, but with the max-hold mode activated. In this case, the power corresponding to different time slots cannot be resolved, but only the maximum power in RBW is measured. A deep explanation of such methods, even though for 4G case (but fundamentals are the same for 5G, modifying specific parameters as bandwidth or central frequency), can be read in [32].

Measurements are done with and without forcing the load of the base station. When an extra load is applied, the extrapolation to the worst-case of exposure requires to compensate the bandwidth difference (eq. (5)).

4.3. Drive test scanner

4.3.1. Basics

There is a recent interest in the literature for using this kind of devices to assess 5G EMF exposure [20,23]. This equipment can resolve the signals received from different base stations and estimate some performance parameters. The SSBs from different base stations can be identified and measured separately. One example of the metrics this equipment provides, is the received signal strength indicator (RSSI), an

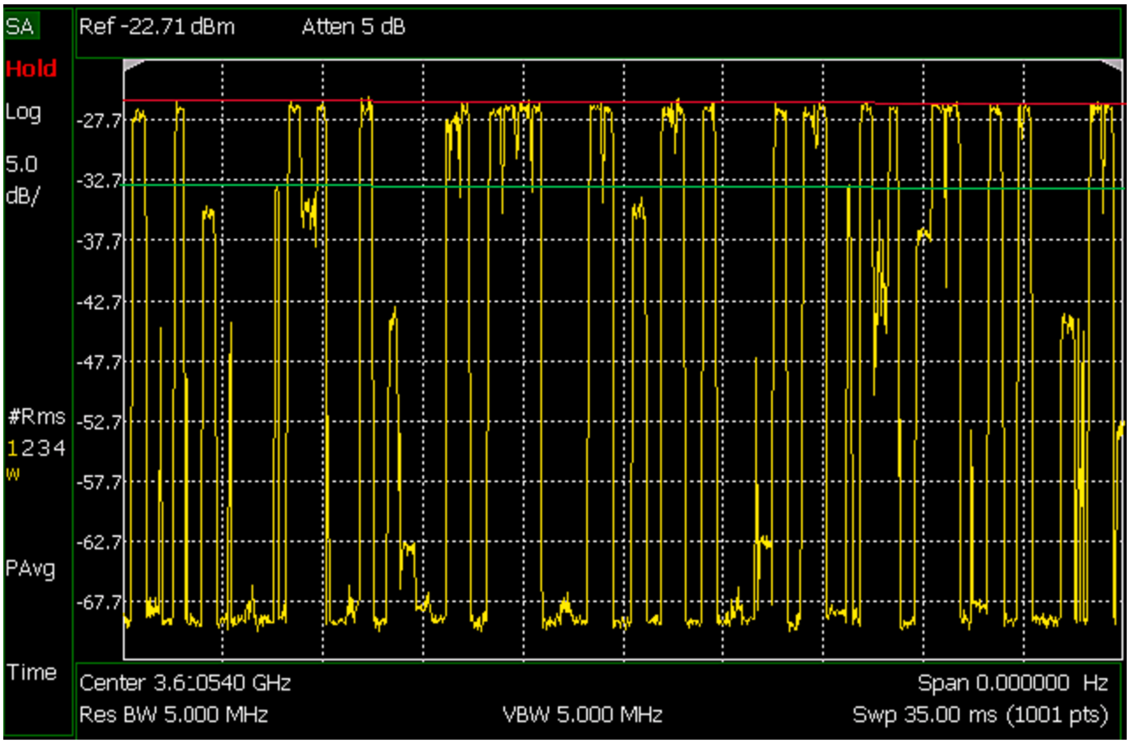


Fig. 7. Zero-span measurement showing SSB (green line at −33.20 dBm) and user data (red line at −26.21 dBm) levels. Note that each measurement point will have specific SSB and user data levels.

average of power level of the different sources detected, including adjacent cells. Another metric is the reference signal received power (RSRP) that is the average of the SSB power received per RE.

The DTS used for this work was an R&S TSME6 drive test scanner and the ROMES 4 software to decode the information and display the measurement results.

4.3.2. *Field assessment*

The first step in the assessment with a DTS is to set SSREF, which can be obtained from SA measurements, as explained before, if not provided by the network operator. The RSRP value will be used to extract the maximum exposure, thus the equipment has to be configured to get this parameter. As with the broadband field meter and the SA, DTS measurements were taken with regular load and forcing a load increase. The RSRP values are expected to be the same as the level of SSB is independent of the user load. Then, the RSRP values have to be converted to the E-field (V/m) by using eq. (4). As the RSRP corresponds to one resource element, i.e. one subcarrier, its field value (E_{RE}) is extrapolated based on the bandwidth of the channel,

$$E_{fullBW} = E_{RE} \bullet \sqrt{\frac{BW_{signal}}{SCS}} \tag{7}$$

It is also necessary to correct the differences between the gains of the SSB and the data, as shown in eq. (6).

4.4. *Measurement environment*

The 5G base station used for the measurements is located in the surroundings of the School of Telecommunication Engineering of the University of Vigo, Spain (42°10′10.87″ N 8°41′14.61″ W). The terrain is a slope in a hill, descending from the top of Fig. 8 to the bottom. Besides the 5G signal, there are other services as in the bands shown in Table 3. Measurements were recorded at 7 locations (shown in Fig. 8), in line of sight (LOS) conditions to the base station. These locations are those where highest field levels were found after an exploratory measurement with the broadband probe around the base. Point 7 was located at the roof of a building and the other at ground level but having different relative heights due to the layout of the area. Data relative to the position of each measurement point with respect to the base station antennas are provided in Table 4.

At each location, 6-minute measurements were simultaneously performed with the different equipment (see Fig. 9) with the load that was managing the station at each moment. Then, they were repeated while forcing the increment in the load of the base station. Finally, 10 instantaneous measurements with both regular load and increased load were done with the SA for the SSB assessment and the estimation of the SSB and data gain correction factor (k_{gain}), as explained in subsection 4.2.3.1 . The resulting gain correction factors are shown in Table 5. These correction factors are different for each location because the gain patterns are different at different positions. Thus, points located at similar distance to the base station can have different correction factors. The effects of the environment and the position with respect to the antenna beam center, which can change depending on the slopes in the area, affect to the power level coming from the signaling beam. And the level of the user beam depends on how the base station configures the

Table 3
Telecommunication bands available in the analyzed base station.

Service	4G	2G/3G	2G/4G	5G
Band (MHz)	832–842	925.1–935.1	1859.9–1879.9	3600–3710

Fig. 8. Location of the 5G base station and the measurement points. Google Earth Pro 7.3.6.9345 (64-bit), Landsat, Copernicus, <http://www.google.com/earth/index.html> (Accessed March 5, 2024).

Table 4
Data of the measurement points location.

Point number	Distance (m)	Azimuth (°)	Height of the Probe (m)
P1	48	171	1.80
P2	82.5	244	1.82
P3	38.5	114	1.77
P4	80	20	1.80
P5	91.5	8	1.74
P6	55	325	1.79
P7	52	350	1.78

beam (the beamforming process) and on the number of users in the network. The distance among antennas of the devices was the minimum to avoid mutual coupling. The decision behind doing the measurements with the different equipment at the same time was to keep the field levels measured by each equipment as close as possible, avoiding temporal fluctuations of the field (especially as we cannot control the number of users in the area which can severely affect the power level of the user beam).

5. Measurement results

To establish comparison among the results obtained with the different equipment and methods we need to estimate the uncertainty of each measurement. Thus, the first subsection introduces some tips for performing such estimation and then, the following subsections present the results obtained with each of the considered procedures.

5.1. Uncertainty estimation

The first step in the process is to list all the probable sources of error with an estimation of their uncertainty and the associated probability distribution. Some guidance on how to elaborate the uncertainty budget for EMF field measurements is given in [33] where some examples are provided with main sources of uncertainty and the associated distribution; they involve:

- Uncertainties associated to the measurement equipment, including those of the calibration laboratory.
- Those associated to the procedure followed to estimate the measurement results.
- The difference in the measured values when the measurement process is performed by different technicians.
- The effect of environmental conditions (temperature, humidity, etc.).

When all the N individual components, $u(x_i)$, are identified and quantified, we can combine them by using the law of propagation of uncertainties [34],

$$u_c(y)^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u(x_i)^2 \tag{8}$$

Finally, the combined standard uncertainty, $u_c(y)$, is multiplied by a coverage factor, k, to obtain an expanded uncertainty, U, which defines an interval around the measured result where the true value of the magnitude is located with a certain confidence level.

$$U(y) = k \bullet u_c(y) \tag{9}$$

Table 5
Gain correction factors at each location.

	P1	P2	P3	P4	P5	P6	P7
Gain difference (dB)	7,01	11,55	1,55	21,57	3,01	14,99	12,04
k_{gain}	2,24	3,78	1,19	11,97	1,41	5,62	4

Fig. 9. Measurement set-up at location 6.

An example of estimation of uncertainty in the process of evaluating human exposure to EMF using a broadband sounder is presented in [14]. However, this research was made before the 5G deployment, and most of the specific characteristics of 5G New Radio schemes are not still considered.

5.2. Broadband field meter results

Fig. 10 shows the values of the RMS E-field at the different locations. Blue points correspond to the measurements without producing an extra load to the station. Green squares represent the values obtained when producing an extra load, corrected from the achieved data rate (see Table 6) to the maximum data rate. We had also performed measurements of the E-field some months before the installation of the 5G systems in the base station. The results are those depicted with the orange diamonds and represent the pre-existing E-fields produced by other communications systems at the same points.

Pre-existing and no extra load E-field values are rather similar, with an average, across the seven locations, of 0.83 V/m. This agrees with measurements done in other countries whose authors conclude that the exposure to 5G signals is limited [23,29,30], but this does not assure the base station compliance as full load situation should be considered for such assessment. It also shows that the increase in the EMF field is due to the induced data traffic.

The values extrapolated to full load show an increase ranging from 0.6 V/m (Point 3) up to 5.18 V/m (Point 7). The highest field value measured, 6.33 V/m, is well below the reference level of 61 V/m [2]. The locations with the lowest level (1 and 3) correspond to those of lower altitude and closer to the base station. In them, probably, the antenna beam illuminates above the measurement position, i.e. we were so close and at an altitude that the antenna beamforming system was not able to point to that locations.

Fig. 11. compares the extrapolated field values (green squares) with the peak values measured when forcing an extra load with the mobile phone (purple triangles). For data rates larger than 40 % of the total base station capacity, the peak values are higher than the RMS extrapolated values. In the other cases, both values are on the same order, except for location 4, where it is significantly lower. This could come from the fact that the downlink data rate achieved during the measurements at that location was low, just around 12 % of the total base capacity.

5.3. Measurement of SSB: Spectrum analyzer vs drive test scanner

The measurement of the E-field associated to the SSB has been accomplished both with the SA and the DTS. Results are shown in Fig. 12. Values from the SA correspond to the maximum power of the SSB obtained from the individual sweeps in the time domain, collected as explained in section IV. Those of the DTS are the RMS of the RSRP values gathered during each 6-minute measurement.

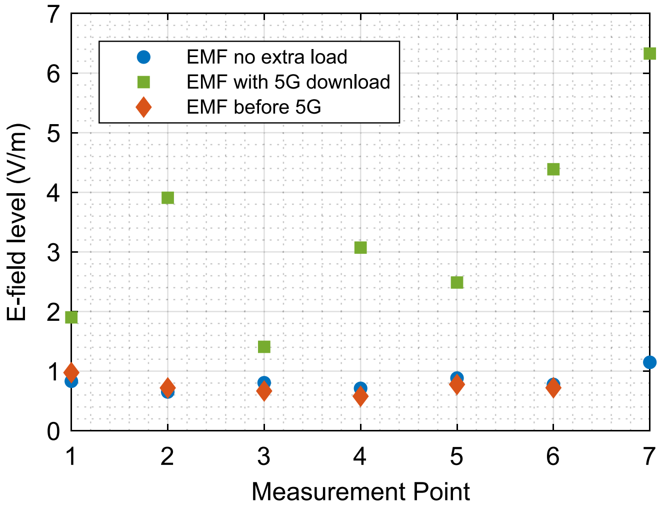


Fig. 10. RMS field values measured with the broadband field meter and an isotropic probe.

Table 6
Summary of the average data rate achieved at each location.

	P1	P2	P3	P4	P5	P6	P7
Data rate (Mbits/s)	156	259	231	46	152	294	183

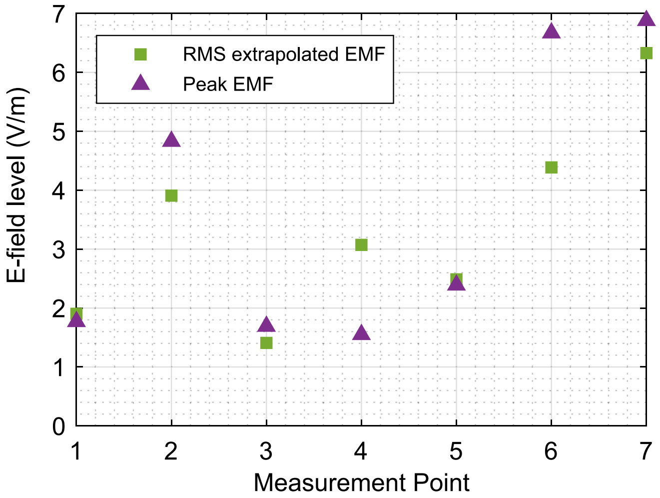


Fig. 11. RMS extrapolated field values vs peak values when forcing the load of the base station.

We have represented the case where we use a terminal to produce an extra load (in orange and green, for SA and DTS, respectively), and the case without producing any extra download (blue and purple). If we consider the measurements done with each equipment, the levels obtained with and without loading the base station are similar, with differences well inside the corresponding uncertainties. When comparing results from both equipment, they match in 5 of the 7 locations. Additional errors due to the pointing of the antennas, or effects of the environment that are not quantified here, could explain that the measurements in the other two locations do not fit in the defined uncertainty intervals. Also, in 5 of the 7 locations the values measured with the SA are higher, which could reflect that this equipment is more likely to overestimate the field level. In view of the results, the SA could also be a good option for measurement procedures based in the extrapolation of the SSB level.

5.4. Broadband field meter measurement versus spectrum analyzer and drive test scanner

Table 7 and Fig. 13 show the EMF field values obtained with the different measurement approaches to estimate the worst-case of exposure (i.e. forcing an extra load of the base station, doing all necessary extrapolations and correcting the SSB and data gain differences).

As happened with the broadband instrument measurements, those performed with the SA and DTS are well below reference level, which is 61 V/m [2]. Field values measured with the SA in max-hold mode match with those of the broadband field meter in 5 of the 7 locations. Measurements at the other two locations correspond to lower data rates, so it could happen that no user data was allocated in the measured bandwidth. This can be appreciated when comparing SA values obtained with no extra load and extra load for those two points (Table 8). The levels obtained in the second case are lower, in contrast to what we expect and

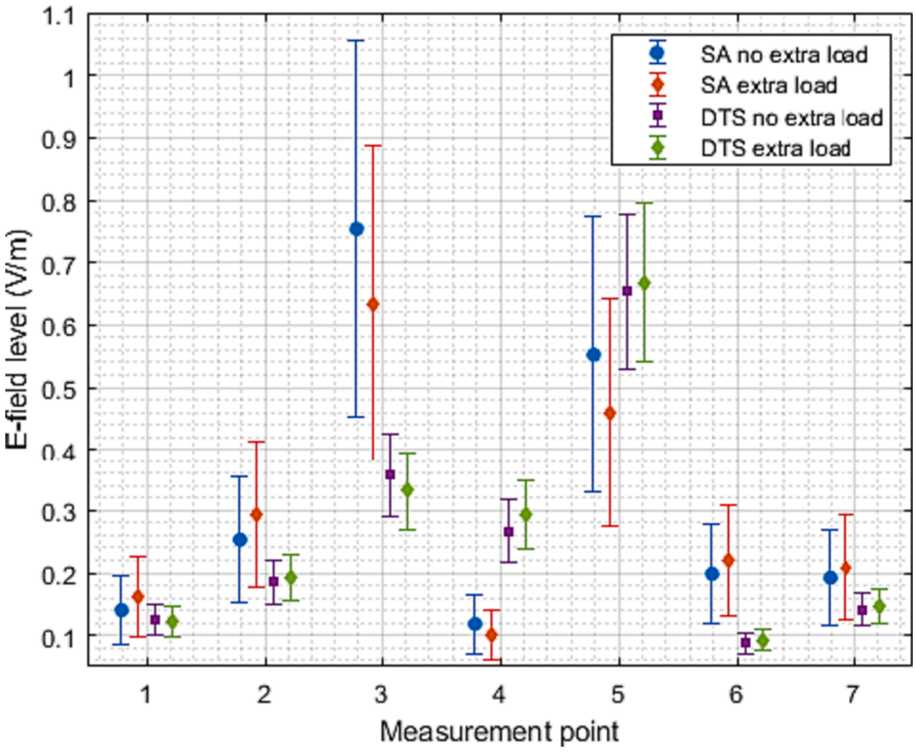


Fig. 12. Comparison of SSB field level assessment with SA and DTS.

Table 7
EMF field values at each location in V/m (worst-case of exposure).

Point number	Broadband instrument	SA Max-Hold	SA SSB	DTS SSB
P1	1.90 ± 0.41	1.93 ± 0.77	1.05 ± 0.42	0.79 ± 0.15
P2	3.91 ± 0.84	4.74 ± 1.89	3.21 ± 1.28	2.11 ± 0.41
P3	1.41 ± 0.31	1.93 ± 0.77	2.18 ± 0.87	1.14 ± 0.22
P4	3.07 ± 0.66	0.39 ± 0.15	3.49 ± 1.40	10.11 ± 1.92
P5	2.49 ± 0.53	1.24 ± 0.50	1.87 ± 0.75	2.72 ± 0.52
P6	4.39 ± 0.95	6.2 ± 2.48	3.57 ± 1.43	1.5 ± 0.29
P7	6.33 ± 1.39	8.81 ± 3.53	2.41 ± 0.96	1.7 ± 0.32

what happen in the other locations, revealing the absence of user data despite the data download. Thus, the downlink data rate must be high enough to guarantee receiving user data in the measurement bandwidth and, consequently, getting higher field levels.

We should also consider that the values provided by the broadband probe are RMS values and those of the SA the maximal values during the 6-minute-measurements. If we compare with the broadband probe peak values instead, results are closer for the locations where higher download data rates were achieved.

If we compare the methods based in the SSB extrapolation with the broadband probe and the SA in max-hold, results match quite well in locations 1, 3 and 5. In locations 2, 6 and 7 the broadband probe and the SA return the highest values. Thus, broadband equipment can still be used for assessing the EMF field level when measurements are done by forcing an extra load of the station, as it uses to overestimate the field levels.

The largest differences in the values measured by the different methods happen at location 7, and especially at location 4. This probably comes from the fact that the assessment based in the SSB level extrapolation requires a compensation of the SSB and data beam gains. The gain correction factor applied was calculated from measurements, thus adding an additional degree of uncertainty.

6. Discussion

Adding the 5G systems does not significantly increase the overall field levels in the surroundings of the base station, in normal working conditions, compared to those of the previous generation. This has been checked during a measurement campaign in the surroundings of a 5G base station under operation.

When assessing the worst-case of exposure, the field levels obtained by applying the different methodologies (broadband field meter, spectrum analyzer and drive test scanner), uncertainty included, resulted to be all significantly below the reference levels [2].

Results show that forcing the base station with an extra load seems to be a solution for assessing human exposure with simple broadband field meters, as the RMS E-field levels match or overestimate the values obtained with other methods. A minimum data rate of at least 40 % seems to be convenient for the peak values to be close to those resulting from the RMS extrapolation. In case these field levels gathered by broadband probes do not comply with the safety limits, measurements should be repeated with more accurate narrowband methods. That approach has already been performed in the past, with previous generations systems, when frequency selective equipment was used only to assess the exposure in locations where broadband field meter tests were inconclusive (i.e. [5]).

Another option when the broadband field meter measured levels overpass the limits could be to directly assess the SSB level with an SA or a DTS. Despite the field level assessment methods that rely in the measurement of the SSB level are least likely to overestimation, they require extrapolation to correct the SSB and data gain differences. If gain differences are not provided by network operators, correction factors could be estimated through measurements. Therefore, measurements of the SSB and of the user data must be done. It is challenging to assure that the

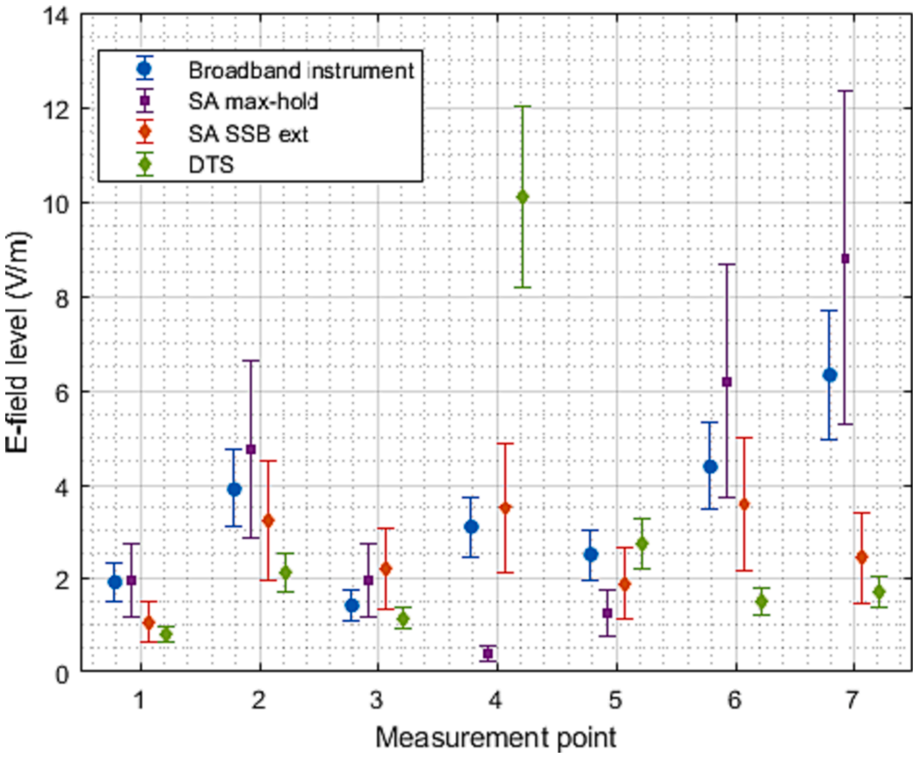


Fig. 13. E-field extrapolated measurement results from the different methodologies.

Table 8
Spectrum analyzer max-hold measurements in V/m.

	P1	P2	P3	P4	P5	P6	P7
No extra load	1.38	2.64	2.38	3.40	1.89	0.89	1.41
Extra Load	1.93	4.74	1.93	0.39	1.24	6.20	8.81

station's user beam is pointing to the measurement position with the maximum gain. This will highly depend on the number of the users in the surrounding at the moment of the measurement and can lead to large errors as shown in the measurements at location 4. The most immediate consequence is that, despite the RSRP measurements done with the DTS are independent from the user load, it has to be used in combination with an SA to be able to correct the SSB and data level difference.

The measurements with the SA in max-hold mode, using the method proposed for LTE [18] adapted to 5G specifications, present some difficulties derived from the 5G option of sharing the SSB bandwidth to transmit user data. On the one hand, if we try to assess the level of the SSB, we could overestimate the values due to the presence of user data being transmitted with a higher level in the SSB frequency band. On the other hand, if we want to estimate the worst-case of exposure by loading the base with a heavy download from a user terminal, we may not be able to achieve a 100 % load, so there is no guarantee of having a user data at the frequency where measurements are being performed.

After discussing the main results obtained, we should also compare the contents of this manuscript in terms of measurement methodologies, cellular generations and consideration of uncertainties during the analysis. Table 9 summarizes the information from various published works.

Typically, broadband field meters with isotropic probes were used in 2G assessment, as it is done by [8] as an example at that time, in which also incipient uncertainty analysis were included when considering the variability with time. Although 3G base station compliance assessment can be made with broadband instruments, there were some works using spectrum analyzers, as in [14]. Most of the 4G assessment works involved narrowband techniques, based on spectrum analyzers [19,32,35,36] or drive test scanners [37]. Besides, some of them compare these results with those provided by a broadband instrument [35,36]. None of them included the three different measurement strategies. Regarding 5G technologies, the use of narrowband systems is

Table 9
Comparison with previously published works.

Reference	System generation	Measurement equipment				Uncertainty assessment
		Broadband instrument	SA	DTS	Other	
[8] 2003	2G	√	x	x	x	partially
[14] 2012	3G	x	√	x	x	√
[13] 2020	4G	√	x	x	x	partially
[19] 2014	4G	x	√	x	x	x
[32] 2021	4G	x	√	x	x	x
[35] 2021	4G	√	√	x	x	partially
[36] 2022	4G	√	√	x	x	√
[37] 2021	4G	x	x	√	x	x
[38] 2021	5G	x	x	x	√ personal exposure meter	√
[39] 2022	5G	x	x	√	x	x
This paper	5G	√	√	√	x	√

generalized [39] or even researchers used specifically designed equipment [38]. Those works only provide results for one measurement system. Thus, to the authors' knowledge, this paper is the first one in completing and comparing measurements with three different strategies, analyzing the performance of each of them and their applicability. Besides that, the uncertainty analysis is not present in many published works.

7. Conclusions

Assessing human exposure to an electromagnetic field in presence of a 5G base station is not an easy task. The implementation of M−MIMO techniques in 5G base stations results in adaptive beamforming. This makes difficult to guarantee that the field levels are at their maximum at the measurement location during the complete measurement period, which would limit the applicability of broadband instruments as having been done for previous generations. In this research, we have compared different methods for 5G exposure assessment, using a broadband field meter with an isotropic probe, a spectrum analyzer and a drive test scanner.

Along the paper, we first give an overview of the 5G signal structure, describing the frequency domain and time domain specifications. Afterwards, possible assessment methods are described. The SSB level is measured using the Keysight FieldFox N9913A SA and the Rohde & Schwarz TSM6 DTS. The values are extrapolated to the worst-case exposure and compared to the measurements done with the Wavecontrol WPF8 broadband field probe. Measurements are repeated increasing the base station load by performing a heavy download from a 5G user terminal located near the testers.

The proposed methods were field tested at the University of Vigo, Spain, with a commercial 5G base station located on its campus. The measurements were performed at 7 locations in LOS conditions around the base station, gathering data with the three different equipment at the same locations and at the same time. This data collection allows the comparison of the three methodologies under the same radiating conditions.

All results have been analyzed considering the specific measurement uncertainties, which allows a deeper and more precise comparison among them.

From the measurement results, we can extract that the exposure levels are low at this stage of the 5G deployment. When loading the base station, the results showed that using the broadband field meter can overestimate the field level. Thus, it is still a useful method to check if the field levels comply with the regulation in human exposure; very simple and cost-effective compared with others. In-situ measurements of human exposure to EMF have to be practical and easy to carry, involving only the resources and equipment strictly necessary, but without compromising the validity of the results. When the reference levels are surpassed, more accurate methods based in the assessment and extrapolation of the SSB level could be a solution. The drawback is the required post processing, specially correcting the gain difference between SSB and data signals. If not provided by the network operator, this difference can be determined through measurements, as explained along this document. Measuring with an SA in max-hold mode in the bandwidth of the SSB does not work in 5G as it does in LTE, as we cannot be sure if the measured level corresponds to the SSB or to the user data, no matter if we are forcing the load of the station or not.

The analysis of the results demonstrate that broadband instruments can be used for assessing human exposure to EMF in the vicinity of 5G base stations, which radiating elements provide fields with extreme fluctuations in their intensity as a function of the system load and beamforming configuration. This is accurate when measurements are done by forcing an extra load of the station and the pointing of an antenna beam towards the probe. The validation of this fast method as a first attempt to assess the compliance of 5G stations permits the testing of these base stations in an efficient way. Only when broadband instrument results (including their uncertainties) would overpass the reference levels, a more detailed analysis would be necessary, which procedure and tips are also depicted along this paper.

CRediT authorship contribution statement

Isabel Expósito: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Cedric Hakizimali:** Data curation, Investigation, Software, Visualization. **Manuel García Sánchez:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Iñigo Cuiñas:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Jo Verhaevert:** Conceptualization, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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