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In-situ Measurement Methodology for the Assessment of 5G NR Massive MIMO Base Station Exposure at Sub-6 GHz Frequencies

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ABSTRACT As the roll-out of the fifth generation (5G) of mobile telecommunications is well underway, standardized methods to assess the human exposure to radiofrequency electromagnetic fields from 5G base station radios are needed in addition to existing numerical models and preliminary measurement studies. Challenges following the introduction of 5G New Radio (NR) include the utilization of new spectrum bands and the widespread use of technological advances such as Massive MIMO (Multiple-Input Multiple-Output) and beamforming. We propose a comprehensive and ready-to-use exposure assessment methodology for use with common spectrum analyzer equipment to measure or calculate in-situ the time-averaged instantaneous exposure and the theoretical maximum exposure from 5G NR base stations. Besides providing the correct method and equipment settings to capture the instantaneous exposure, the procedure also comprises a number of steps that involve the identification of the Synchronization Signal Block, which is the only 5G NR component that is transmitted periodically and at constant power, the assessment of the power density carried by its resources, and the subsequent extrapolation to the theoretical maximum exposure level. The procedure was validated on site for a 5G NR base station operating at 3.5 GHz, but it should be generally applicable to any 5G NR signal, i.e., as is for any sub-6 GHz signal and after adjustment of the proposed measurement settings for signals in the millimeter-wave range.

INDEX TERMS 5G, radiofrequency electromagnetic fields (RF-EMF), exposure assessment, measurement, massive MIMO, mobile telecommunications, new radio, spectrum analyzer.

I. INTRODUCTION

The introduction worldwide of the fifth generation (5G) of mobile telecommunications [1] is well underway. In contrast to second to fourth generation (2G–4G) mobile technologies (such as Global System for Mobile communications (GSM), Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE)), the 5G New Radio (NR) technology will make use of a huge span of radiofrequencies (RF), split in two broad ranges: one spanning from 410 MHz to 7.125 GHz ('sub-6 GHz'), and the other from 24.25 GHz to 52.6 GHz ('mmWaves'). Furthermore, one of the main technological advances introduced or enhanced in 5G NR will be the widespread use of Massive Multiple-Input Multiple-Output (MaMIMO), in which many antenna elements (up to hundreds) can be used to narrow and steer the transmit beam in order to optimize the signal at the receiver device.

Guidelines on limiting the human exposure to electromagnetic fields (EMF) have been issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) based on decades of scientific

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TABLE 1. Constant-power signal components of second through fifth generation telecommunications technologies.

(Generation) Technology	Constant-power component(s)
(2G) GSM	BCCH (Broadcast Control Channel)
(3G) UMTS/CDMA	CPICH (Common Pilot Channel)
(4G) LTE	CRS (Cell-specific Reference Signals), primary synchronization signal (PSS) and secondary synchronization signal (SSS), and physical broadcast channel (PBCH)
(5G) NR	PSS, SSS, and PBCH (i.e., 'SS/PBCH block' or 'SS block')

research [2], [3]. These guidelines have formed the basis for recommendations by internationally recognized institutions such as the World Health Organization (WHO), the US Federal Communications Commission (FCC) [4], and the International Telecommunications Union (ITU), as well as the Recommendation of the European Council [5]. However, some countries or regions (such as Brussels, Belgium) have adopted their own, more strict legal regulations, which may delay or even impede the deployment of 5G networks due to EMF saturation where current limit levels have already been reached with pre-5G telecommunications infrastructure [6]–[9].

In the last few years, there have been a few publications discussing how to properly assess the exposure levels from 5G base stations [10]–[15], some of which include numerical studies and preliminary measurements. However, as of yet, there is no standardized method available.

EMF exposure assessment methods for time-variant mobile telecommunications signals have relied on the measurement and subsequent extrapolation of user-independent signals that are transmitted continuously (or periodically) at constant power, independent of the traffic load [16]–[18]. These signals differ from one telecommunications technology to the other (Table 1): i.e., the Broadcast Control Channel (BCCH) for GSM, the Common Pilot Channel (CPICH) for UMTS, and the cell-specific reference signal (CRS), synchronization signals (SS) and physical broadcast channel (PBCH) for LTE. In the case of NR, there is no CRS, but the 'always-on' signal components are, as in LTE, the primary and secondary synchronization signals (PSS and SSS) and the PBCH. The PSS and SSS are used by user devices to find, identify, and synchronize to a network, while the PBCH contains a minimum amount of system information. Together, these signals form the SS/PBCH block (also denoted as SS block or SSB).

Although previous studies (e.g., [14], [15]) have discussed extrapolation methods based on measuring the power of the SSB, none have been molded into a feasible assessment methodology, nor have they been tested in the field.

This paper presents a comprehensive description of a measurement methodology to assess the RF-EMF exposure of a 5G NR base station on site. First, we describe the main principles of the 5G NR physical layer that are important for an accurate assessment. Second, we introduce and discuss the proposed measurement equipment and methods to measure or calculate the time-averaged instantaneous exposure and the theoretical (and actual) maximum exposure. And lastly, the proposed methodology was validated *in-situ* in the vicinity of a 5G NR base station operating at 3.5 GHz in Düsseldorf, Germany.

II. 5G NEW RADIO AND RF-EMF EXPOSURE

The accurate assessment of an RF signal requires that the settings of the measurement device be optimized to the characteristics of the considered signal. Here, we discuss the main principles of the physical layer of 5G NR that are important for RF exposure assessment. More detailed information is out of the scope of this paper but can be found in the 3GPP technical specifications [1].

A. 5G NR GRID STRUCTURE

Like 4G LTE, 5G NR supports both frequency division duplexing (FDD) and time division duplexing (TDD) and signals are modulated by using Orthogonal Frequency Division Multiplexing (OFDM) with a cyclic prefix. Moreover, 5G NR also uses a grid structure consisting of subcarriers in the frequency domain and OFDM symbols in the time domain. The basic granularity of the 5G NR resource grid (i.e., in frequency and time) is the resource element (RE), which spans one OFDM symbol in time and one subcarrier in frequency.

In the frequency domain, the grid structure is further organized in resource blocks (RBs), with each RB consisting of twelve contiguous subcarriers. The total number of RBs available for data transmission (N_{RB}) depends on the channel bandwidth (up to 100 MHz for sub-6 GHz signals) and the numerology or sub-carrier spacing (SCS), which is 15 kHz, 30 kHz, or 60 kHz for sub-6 GHz signals. This is in contrast to LTE, where the SCS is fixed at 15 kHz and the bandwidth at up to 20 MHz.

In the time domain, the structure is organized in frames. A 5G NR radio frame is 10 ms long and consists of ten subframes of each 1 ms. A subframe is further divided into slots, which each comprise 14 (in the case of a normal cyclic prefix) or 12 OFDM symbols (in the case of an extended cyclic prefix). The number of slots and the duration of a symbol depend on the SCS. For example, in the case of an SCS of 30 kHz, a subframe consists of two slots and the symbol duration is 35.68 μs. Analogous to an RB in the frequency domain, a slot is the basic transmission unit in the time domain.

The SS/PBCH block, which comprises the constant-power signal components of 5G NR, spans four OFDM symbols in the time domain and 240 contiguous subcarriers, or 12 RBs, in the frequency domain (Fig. 1). As opposed to the constituting signal equivalents in LTE, in 5G NR the SSB is not fixed to the center frequency of the radio channel, but instead its position (denoted by SS_{REF}) is determined by the Global Synchronization Raster Channel (GSCN) value, which fixes

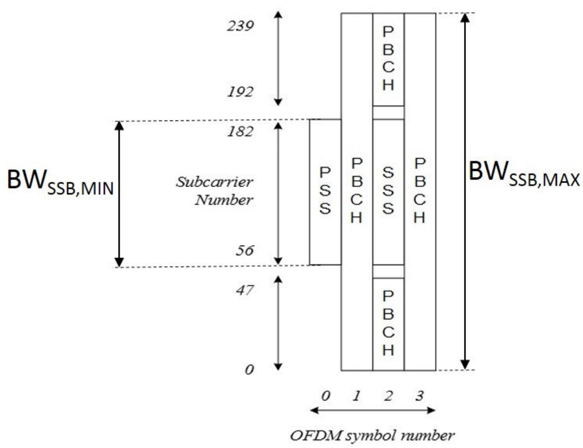

FIGURE 1. Structure of the SS/PBCH block in time and frequency, with indication of the minimum ($BW_{SSB,min}$) and maximum bandwidth ($BW_{SSB,max}$).

it on a discrete raster. Furthermore, whereas in 4G LTE the synchronization signals are transmitted over the entire cell, 5G NR systems can apply beamforming, in which case the base station repeatedly transmits the SSB in a number of predefined directions (or beams) in an SS burst or SS burst set (consecutive SS bursts). The SS burst (set) is transmitted at regular time intervals, which can be 5, 10, 20, 40, 80 or 160 ms (with the default being 20 ms), within the span of one half-frame (5 ms) [1].

B. TIME-AVERAGED INSTANTANEOUS EXPOSURE

Assessment of the time-averaged instantaneous exposure level E_{avg} of an RF signal means measuring the actual, instantaneous electric-field strength over the entire signal channel bandwidth during a certain time and subsequently taking the average. For example, for comparison to the ICNIRP limits (both basic restrictions and reference levels), we should measure for 6 min [2], and for IEEE 30 min [3]—although, in practice, a shorter measurement time (e.g., 1 min per component) is often sufficient to derive an exposure value representative of longer averaging times [19], [20]. This is a straightforward measurement, although one must be careful to use the correct settings, which are signal-specific [17], [21].

C. THEORETICAL MAXIMUM EXPOSURE

The exposure level at an evaluation point in line of sight (LOS) of a 5G NR base station will reach the maximal value when the traffic load is at its maximum (i.e., when the 5G NR frame is completely filled with downlink data) *and* all traffic is transmitted at the maximum possible gain G_{max} in the direction of the evaluation point. Then, to obtain the worst-case (*theoretical maximum*) exposure level E_{max}, the electric-field strength per RE of the dominant SSB beam ($E_{RE,SSB}$) is extrapolated based on the bandwidth of the channel and the radiation pattern of the traffic beam(s):

$$E_{max} = \sqrt{\alpha}\,\sqrt{12N_{RB}}\,E_{RE,SSB}, \qquad (1)$$

where N_{RB} is the number of resource blocks available over the 5G NR channel bandwidth (e.g., 273 for a signal with SCS 30 kHz and BW 100 MHz), and

$$\alpha = \frac{G_{max}}{G_{SSB}} \qquad (2)$$

is the ratio of G_{max} to the gain of the dominant SSB, G_{SSB}. This ratio has to be derived based on the pattern of the base station product. Additional information is provided in Section IV-F.

D. ACTUAL MAXIMUM EXPOSURE

Since (1) assumes that the radio frame is fully occupied (i.e., at 100% slot occupation) with downlink traffic and broadcast/control data which is all continually transmitted at the highest possible gain in the direction of the evaluation point, E_{max} represents an unrealistic overestimation of the exposure level [11], [14], [15]. Whereas this value might have had its use for previous technologies, in reality, due to the increased variability of the usage in space and time, it is unrealistic for a 5G NR base station to transmit at its maximum power *and* to concentrate all of its power in a single beam during an extensive amount of time (e.g., 6 min, the averaging time required by the ICNIRP guidelines [2]). By taking into account additional factors such as the base station utilization, the spatial distribution of energy during a certain time, as well as a downlink duty cycle (in the case of TDD), one can calculate a more realistic, *actual* maximum exposure level. Refs. [11], [17], [22] provide further information on the assessment of the actual maximum exposure.

III. PROPOSED MEASUREMENT PROCEDURE

A. OVERVIEW OF 5G NR ASSESSEMENT PROCEDURE

The proposed measurement methodology consists of five steps:

- *Step 1 "Spectrum overview"* — We perform an overview measurement of the telecommunications frequency range to identify the RF signals that are present at the measurement location and in particular the 5G NR signal from the base station under test.
- *Step 2 "Locating the SS burst"* — An important step in the assessment of a 5G NR signal based on extrapolation of the SSB power, is the determination of the actual location of the SS burst. In this step, we identify SS_{REF} as well as the numerology of the SSB(s).
- *Step 3 "Obtaining the field level per RE of the SSB"* — We measure the electric-field strength per resource element of the dominant SSB, $E_{RE,SSB}$.
- *Step 4 "Measuring the instantaneous field level"* — We determine the time-averaged instantaneous electric-field strength over the channel bandwidth, E_{avg}, measured during a certain time, T_{avg} (e.g., 6 or 30 min).
- *Step 5 "Post-processing"* — We extrapolate $E_{RE,SSB}$ to the theoretical maximum exposure level E_{max} by using (1). We then compare the obtained exposure levels with the relevant exposure limits such as those proposed

TABLE 2. Spectrum analyzer settings for sub-6 GHz 5G signals.

	SA mode	CF	Span [MHz]	Detector	RBW [MHz]	SWT [s]	Number of sweep points	Sweep mode	Measurement time[a] [s]
Step 1	frequency	3350 MHz	5300	peak	0.3	177[b]	17667	max-hold	177
Step 2	frequency	CF of 5G NR channel	100	rms	1	14.4×10^{-3}	101	actual	20
Step 3	zero-span	SS_{REF}	0	rms	1	x[c]	32001	actual	60
Step 4	zero-span	depends on $\mathrm{RBW_{SA}}$[d]	0	rms	$\mathrm{RBW_{SA}}$	60	376[e]	actual	360[f]
	frequency	CF of 5G NR channel	100	rms	1	y[g]	101	actual	360[f]

CF = center frequency, RBW = resolution bandwidth, SWT = sweep time, SS_{REF} = CF of SS/PBCH block, $\mathrm{RBW_{SA}}$ = maximum resolution bandwidth of the SA, rms = root-mean-square.
[a]Per vector component of the electric field, except for Step 2, for which only one component has to be measured.
[b]The measurement time per sample is the duration of one 5G NR frame (i.e., 10 ms). If the measurement time per sample would be too short, signals could be missed and it would take too much time to build up the spectrum.
[c]x = 32001 × SSB symbol time, such that the measurement time per sample is equal to the SSB symbol time.
[d]Repeated k = 100 / $\mathrm{RBW_{SA}}$ times, using CF = $f_s + (l + \frac{1}{2})RBW_{SA}$, with $l = 0 \ldots k-1$, and f_s is the start frequency of the considered 5G NR signal.
[e]The measurement time per sample is the maximum SS burst period (i.e., 160 ms).
[f]Six minutes is the averaging time recommended by ICNIRP [2], but the actual measurement time can be shorter if the signal is deemed stable [19], [21].
[g]y = 101 × SS burst period, such that the measurement time per sample is equal to the SS burst period. If not known, take the maximum SS burst period of 160 ms.

by ICNIRP [2] of IEEE [3] (in this case, the reference levels for the electric-field strength). Furthermore, we can calculate the actual maximum exposure in case additional deduction factors are known (Section II-D).

While 5G NR demodulation software can assist in locating the SSB, identifying its numerology, and measuring its power per RE [15], we focus in this paper on a procedure usable with a common spectrum analyzer (SA). The general method outlined here remains the same in either case.

Finally, the specific steps to be taken depend on the objective of the measurement. If the only objective is to determine the maximum theoretical exposure, step 4 is unnecessary. Likewise, only steps 1 and 4 are needed if the time-averaged power is the sole quantity of interest.

B. SPECTRUM ANALYZER MEASUREMENT SETUP

The measurement setup used for this study consisted of a Rohde & Schwarz FSV spectrum & signal analyzer FSV30 connected to a Clampco Sistemi AT6000 tri-axial antenna. An SA setup measures the received power P (dBm) of a signal, which is then converted to an electric-field value E (V/m) by using the antenna factor AF (dB/m):

$$E = \frac{1}{\sqrt{20}} 10^{\frac{P+AF}{20}} \tag{3}$$

In order to capture the total electric-field level, all three orthogonal components (X, Y, and Z) of the electric-field vector are to be measured. In this study, they were evaluated sequentially by internally switching the respective axis of the Clampco antenna.

Furthermore, the R&S FSV30 was equipped with option R&S FSV-K14 to use it in 'spectrogram mode'. Besides offering a graphical overview of successive measurement sweeps or traces as a function of time (i.e., the 'spectrogram'), this option also allowed us to store a high number of measurement traces (up to 20,000 for the R&S FSV-30) and exporting them with a minimum of lag or 'blind time'.

The SA settings proposed for each step of the measurement procedure can be found in Table 2 and will be discussed in the following section. It is important to note that the mentioned settings may be specific to our measurement equipment, and equivalent settings for other equipment can be used.

C. DISCUSSION OF MEASUREMENT SETTINGS

1) SA SETTINGS FOR STEP 1

In the first step, a spectrum overview measurement is used to identify the RF signals present in the frequency range used by telecommunication signals (e.g., 700 MHz – 6 GHz). The proposed settings can be found in Table 2.

In order to distinguish between different telecommunication signals (2G–5G), the resolution bandwidth (RBW) is set to a value approximating the minimal bandwidth of the existing telecommunications signals, which is 200 kHz (used by 2G). By using a peak detector in combination with a long sweep time (SWT) and maximum-hold mode, and measuring until the display of the SA is relatively stable, all non-continuous but repetitive signals present at the measurement location are detected. The measurement time per sample is set equal to the duration of one 5G NR radio frame (i.e. 10 ms), by configuring the SWT accordingly.

It is important to note that, with these settings, the measured power levels provide only an indication of the peak values (typically a large overestimate due to the effect of modulation) and no further conclusions can be made.

2) SA SETTINGS FOR STEP 2

After the present 5G NR channel(s) is/are identified, the frequency positions of their broadcast signals are located. If, at the location of assessment, SS_{REF} and the SSB numerology (which defines the BW of the SSB) were not provided by the operator and thus unknown, they can be determined using the following measurement (settings in Table 2).

The center frequency (CF) of the considered 5G NR channel is obtained from the previous step (or from operator information). The frequency span is set to 100 MHz, which is the largest BW for sub-6 GHz 5G NR signals, and the RBW to 1 MHz, as this is the widest possible setting for our measurement setup narrower than the minimum bandwidth of the SSB (i.e., $BW_{SSB,min} = 1.9$ MHz for SCS 15 kHz; Fig 1). Furthermore, the measurement time per sample or sweep point is set to 143 μs, which is the shortest duration of the SSB in case of sub-6 GHz 5G NR signals (SCS 30 kHz). In combination with 101 sweep points, this corresponds to an SWT of 14.4 ms.

In the absence of traffic, which may be transmitted at a higher gain than the broadcast signals, these settings result in the highest power levels when the SA sweeps the (exact) frequency and time range of an SSB, i.e., when within the measurement time per sample, exactly two (SCS 15 kHz) or four symbols (30 kHz) were transmitted at the same power. Hence, by plotting the maximum power per frequency over all measurement traces, we are able to identify the SSB frequency range.

3) SA SETTINGS FOR STEP 3

Thirdly, the power distribution of the REs that are part of the SSB is determined. As we are looking for a recurrent signal of a certain duration (which depends on the structure of the SS burst [1]), aligning measurement samples in time should show us when the SS burst was transmitted. Then, we retain only those samples that were measured during the dominant SSB of the SS burst. The proposed settings for this measurement can be found in Table 2.

In order to continuously measure the power received in the SSB frequency range, we opt for a zero-span measurement, i.e., a measurement of the received power within a certain frequency band as a function of time, with SS_{REF} as CF and an RBW that is smaller than or equal to $BW_{SSB,min}$ (Fig. 1) [15]. To average out the variations in time (due to OFDM modulation [15]) and in frequency, a measurement time per sample about equal to the symbol time of the SSB and an RBW of at least 1 MHz are proposed, in combination with an root-mean-square (rms) detector (Table 2). Finally, to determine the power per RE (i.e. over a BW equal to the SCS), a deduction factor

$$f_{BW} = 10\log_{10}(RBW/SCS) \tag{4}$$

has to be applied to the resulting power measurements.

4) SA SETTINGS FOR STEP 4

The time-averaged instantaneous electric-field strength can be measured with an SA in both frequency and zero-span mode. The proposed settings for both measurements can be found in Table 2.

Depending on the SA specifications, it is possible to measure a 100-MHz bandwidth signal at once in frequency mode. In this case, E_{avg} is determined by calculating the average of the field levels of N successive measurement traces, E_j ($j = 1 \ldots N$), spanning a time much longer than the duration of a 5G NR radio frame (10 ms):

$$E_{avg} = \sqrt{\sum_{j=1}^{N} \frac{E_j^2}{N}}. \tag{5}$$

In zero-span mode, on the other hand, the RBW of most commercially available SAs is too narrow to completely contain the signal spectrum within the passband of the instrument (e.g., for the FSV30, the maximum RBW is 28 MHz in zero-span mode). In this case, the measurement is split in a number of contiguous parts to cover the whole channel bandwidth of the 5G NR signal. For each part k, the time-averaged field level $E_{k,avg}$ over M_k successive samples is calculated as follows:

$$E_{k,avg} = \sqrt{\sum_{i=1}^{M_k} \frac{E_i^2}{M_k}}, \tag{6}$$

after which $E_{k,avg}$ are summed to obtain the total time-averaged field level E_{avg}.

IV. IN-SITU VALIDATION

A. DESCRIPTION OF THE LOCATION AND TESTS

The proposed exposure assessment methodology was validated in LOS of a 5G NR base station, operating at 3.5 GHz, situated on the upper level of a parking building in Düsseldorf, Germany, on 28 May 2019 (Fig. 2). This site was chosen as it was available for testing purposes and the location was suitable to conveniently position the measurement equipment. The base station antenna was situated at a height of about 12 m above the floor level. The amount of car traffic during the measurements was minimal and assumed to have no influence on the measurements.

Although the base station was not part of a commercial network, one user equipment (UE) was available for testing purposes. We investigated six test cases, described in Table 3. First, Steps 1 and 2 procedure were followed in the case without UE and thus without traffic (T1). Then Steps 3 to 5 of the procedure were validated with three representative use cases, namely a voice call (using WhatsApp, T2), a video call (WhatsApp, T3), and video streaming (on YouTube, T4), and with downlink and uplink traffic forced at 100% capacity (by using the iPerf tool, https://iperf.fr/) of the base station (T5) and the UE (T6a and T6b in Table 3), respectively.

Most of the tests (T1 to T6a) were conducted at Pos. 1, at a distance of 62 m to the base station antenna and

TABLE 3. Description of the performed tests, measurement results of the average electric-field strength (E_{avg}) and the field strength per resource element ($E_{RE,SSB}$), and extrapolation of the latter to the theoretical maximum electric-field strength (E_{max}).

Test	Pos.	Description	$E_{RE,SSB}$ [V/m]	E_{max}[a] [V/m]	E_{avg} [V/m] Zero-span	Frequency
T1	1	No UE	n.m.	n.m.	n.m.	n.m.
T2	1	Voice call [WhatsApp]	0.067	5.537	0.320	0.342
T3	1	Video call [WhatsApp]	0.066	5.455	0.326	0.379
T4	1	Video stream [YouTube]	0.065	5.372	0.288	0.328
T5	1	100% DL [iperf]	0.065	5.372	3.716	3.907
T6a	1	100% UL [iperf]	0.067	5.537	n.m.	n.m.
T6b	2	100% UL [iperf]	0.032	2.645	n.m.	n.m.

DL = downlink, UL = uplink, n.m. = not measured
[a]Extrapolation by using (1), with $N_{RB} = 106$ and assuming $\alpha = 10$.

FIGURE 2. **Measurement site in in LOS of a 5G NR base station situated on the upper level of a parking building in Düsseldorf, Germany.**

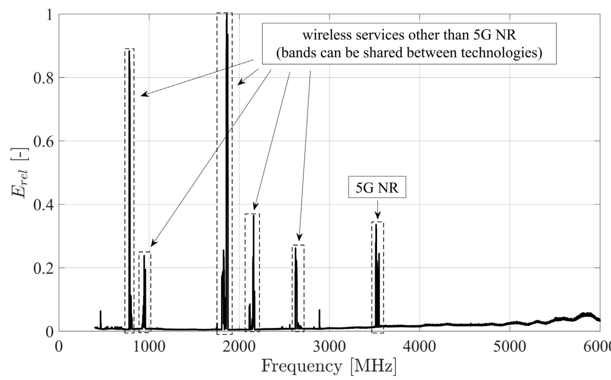

FIGURE 3. **Overview measurement at Pos. 1 during T1 (Table 3), showing as a function of frequency the electric-field strength relative to the maximum measured field strength (E_{rel}). (The used settings (Table 2) do not allow us to accurately measure the field strength, hence this type of measurement can only be used to identify the present RF signals.) Besides a number of earlier-generation mobile telecommunications signals, a 5G NR signal is identified at approximately 3.52 GHz.**

approximately 7 m to the UE. To explore the influence of the UE, another test with 100% uplink (T6b) was conducted at Pos. 2, at a distance of approximately 3 m to the UE and 66 m from the antenna, and at a different azimuth angle to the base station. The height of the measurement probe was 1.5 m above floor level.

The base station was set to operate constantly with a fixed beam in order to validate the methodology in a well-controlled environment.

B. STEP 1 – OVERVIEW MEASUREMENT

First, we performed a spectrum overview measurement (with settings of Table 2) at Pos. 1 during T1. As can be seen in Fig. 3, the RF signals observed at this location included earlier-generation mobile telecommunications signals in the frequency range 700–2700 MHz (i.e., frequency bands around 800 MHz, 925 MHz, 1800 MHz, 2100 MHz, and 2600 MHz), a few other, non-identified signals at frequencies of up to about 3 GHz (at 460 MHz and 2880 MHz), and finally, a 5G NR signal at approximately 3.52 GHz.

It should be noted that the specific frequency allocations are dependent on the country and mobile operator. Parts of the frequency spectrum are auctioned by the government, and the operators themselves choose which bands they employ for which technologies.

C. STEP 2 – LOCATING THE SS BURST

The second step consisted in locating the CF of the SS burst, SS_{REF}. Fig. 4 depicts for each field component the maximum power levels measured per frequency during T1, using the SA with settings of Table 2 and with CF 3.52 GHz.

With the proposed approach, a 7-MHz wide bump in the spectrum was observed on the left side of a 40-MHz wide 5G NR channel (Fig. 4). With no data traffic assumed (since the UE was not connected) the characteristics of this bump (i.e., CF of 3516 MHz and width of about 7 MHz) reveal not only the approximate position of the SS burst but also its SCS: as the 20 RBs of the SSB cover 7 MHz, the SCS was 30 kHz. Furthermore, we obtained the bandwidth of the 5G NR signal, which was 40 MHz. In Fig. 4, we also show two 7-MHz bandwidth parts corresponding to GSCN values of 7857 (black dashed lines) and 7858 (red dotted lines). It is immediately clear that we can distinguish the former as the *only* candidate, and thus $SS_{REF} = 3516.96$ MHz.

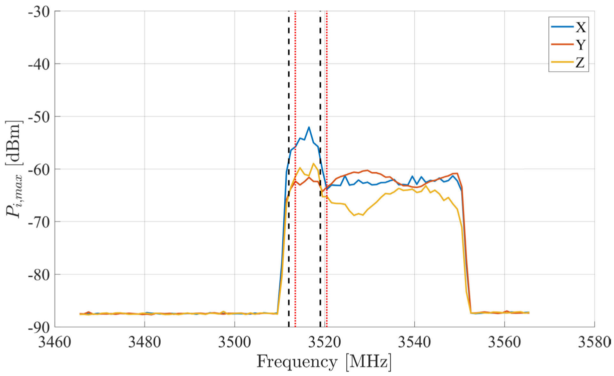

FIGURE 4. Maximum-hold measurement of the power levels per field component as a function of frequency within a 100 MHz range around the CF of the identified 5G NR signal (3.52 GHz) to identify the approximate CF (3516 MHz) and bandwidth (7 MHz) of the SS burst. The black dashed lines indicate a 7-MHz bandwidth around 3515.52 MHz (GSCN = 7857), whereas the red lines indicate a 7-MHz bandwidth around 3516.96 MHz (GSCN = 7858). It is clear that the former is the *only* possible candidate and that we can identify SS_{REF} with this type of measurement.

D. STEP 3 – ELECTRIC-FIELD STRENGTH PER RESOURCE ELEMENT OF THE SSB

To determine the electric-field strength per RE of the SSB, zero-span measurements were performed for each UE test (T2–T6b, Table 3) with an RBW of 1 MHz, a CF of 3515.52 MHz, and a measurement time per sample of 35.63 μs, i.e., one symbol for an SCS of 30 kHz (Table 2). By plotting the measurement samples such that the x-axis holds two radio frames of 10 ms, or 560 symbols, and successive two-frame periods are stacked along the y-axis, while the color of the pixel indicates the power P received by the SA averaged (RMS detector) over the duration of one symbol, one can visualize the diversity and periodicity of the 5G NR signal components that are transmitted within the measured bandwidth (we call this a 'waterfall reconstruction').

Three examples are shown in Fig. 5, depicting waterfall reconstruction plots of measurements during 1 s (50 times two radio frames) of the X-component of the electric-field vector for tests T3 and T5 at Pos. 1 (Table 3). A fourth example (Fig. 6) depicts the results for the 100% uplink test at Pos. 2, which was closer to the UE, and further from the base station.

Located in subframe 0 of the first frame in Figs. 5 and 6, a four-symbol-long SS burst was identified—so in this case, there was indeed only one, cell-wide SSB beam—and its default 20-ms period confirmed. The received rms powers per symbol of the (one and thus dominant) SSB were gathered from all captured traces (roughly 56 per electric-field component when measuring during 1 min, Table 2), and after applying a deduction factor $f_{BW} = 15.2$ dB to the median, the electric-field strength per RE and per component was calculated by using (3). Finally, the median total electric-field strength per RE, $E_{RE,SSB}$, was obtained by adding the three vector components (Table 3).

Whereas we measured an $E_{RE,SSB}$ of about 0.065 V/m consistently during all UE tests at Pos. 1 (T2 to T6a, Table 3), Test T6b (Fig. 6) was performed further away from the base station and closer to the edge of the antenna's main beam,

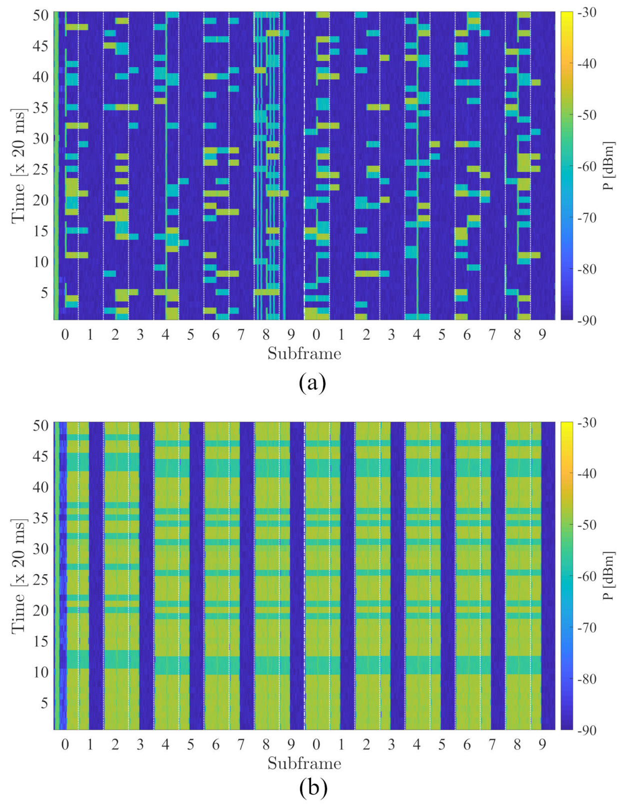

FIGURE 5. 'Waterfall reconstruction' plots of measurement traces of the X-component of the electric field during tests T3 (a) and T5 (b) (Table 3). Differences in pixel color reflect differences in received power P (in dBm) within the 1 MHz bandwidth around SS_{REF}. Consecutive two-frame measurement periods (each 20 ms) are stacked on top of each other, while on the x-axis, the labels show the subframe number within two radio frames. Periodic signals are observed in subframe 0 of the first frame with a period of 20 ms and a length of four symbols—this is the SSB. Five more periodic signals (shorter than four symbols) are present in subframes 8 and 9 of the first frame, possibly corresponding to other control/broadcast signals. During test T3 (a), when a video call was set up, downlink traffic data was observed in random slots (each 14 symbols long) across the grid. Furthermore, during test T5 (b), 100% downlink load conditions were forced on the base station, which resulted in the allocation of roughly three out of four slots to downlink resources.

which resulted in a lower $E_{RE,SSB}$ (Table 3). Furthermore, in Fig. 6 we can observe the presence of the uplink traffic signals in the measurements. Hence, at this distance from the UE (~3 m), UE uplink traffic will have an influence on measurements that assess the time-averaged instantaneous exposure from the base station (i.e., Step 4).

To validate the method described above, we also calculated $E_{RE,SSB}$ based on measurements of the Reference Signals Received Power (RSRP, i.e., the power of the REs of the PSS and SSS) using an R&S TSME scanner with ROMES 5G demodulation software. The result was a median $E_{RE,SSB}$ of 0.059 V/m, which was very close to the values obtained with Step 3 (Table 3).

E. STEP 4 – INSTANTANEOUS ELECTRIC-FIELD STRENGTH

The time-averaged instantaneous electric-field strength E_{avg} was measured with the SA both in frequency and zero-span mode (Table 3). The deviation between the two options

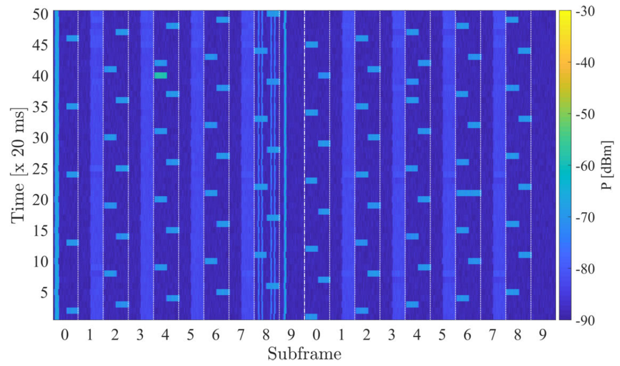

FIGURE 6. 'Waterfall reconstruction' plot of a measurement trace of the *X*-component of the electric field during test T6b at Pos. 2 (Table 3). During this test, the UE was forced to 100% uplink (using iPerf), with roughly one out of four slots of the 5G NR channel allocated to uplink resources.

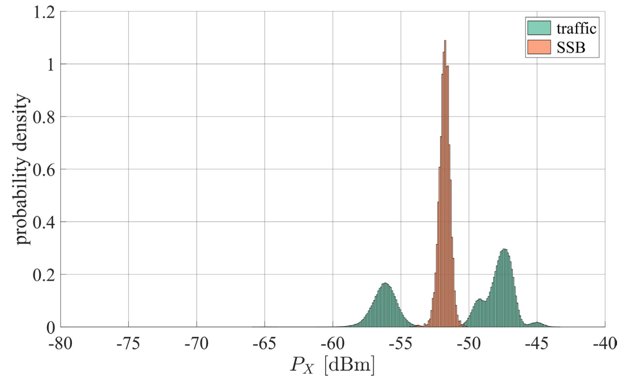

FIGURE 7. Histogram of the total power (of the *X*-component of the electric field) captured over 1 MHz (or 34 subcarriers) per symbol for SSB (in orange) and traffic signals (in green) during T5 (iPerf 100% downlink, Table 3).

ranged between 0.4 dB and 1.3 dB, with frequency-mode measurements resulting in higher field values.

The instantaneous exposure levels (measured in zero-span) ranged from 0.288 V/m (video streaming, T4) to 3.716 V/m (at 100% downlink load, T5), with the latter reflecting a worst-case downlink exposure scenario. In comparison to the scenarios with a single UE, the exposure level was about 130 to 170 times higher when the 5G NR channel was fully occupied with downlink resources (T5) (Table 3). In any case, all values were well below the ICNIRP/IEEE reference level of 61 V/m at 3.5 GHz [2], [3].

F. STEP 5 – POST-PROCESSING

1) TIME-DIVISION DUPLEXING

In Figs. 5 and 6, the difference in the occurrence of traffic data between the tests can be observed. The allocation of downlink traffic is variable in Fig. 5(b), and whereas Fig. 5(b) shows that roughly three out of every four slots (in fixed subframes) were allocated to downlink traffic, from Fig. 6 we observe that slots allocated to uplink traffic were essentially complementary, barring a few slots that were allocated to neither (e.g., last slot of subframe 9). From these results (29 downlink slots out of 40), we obtain a factor $F_{TDD} = 0.725$ for downlink.

2) DIFFERENCE IN GAIN BETWEEN SSB AND TRAFFIC

Since we can distinguish SSB signals from traffic signals in the measurements of Step 3 (Fig. 5), it is possible to derive an approximation of the maximum gain difference between broadcast and traffic beams.

In Fig. 7, we compared the distributions of the SSB (orange) and the traffic samples (green) for the *X*-component of the electric field. Whereas the SSB samples follow one Gaussian distribution (with median −51.9 dBm), the traffic samples follow a mixture of three Gaussian distributions (and a smaller fourth). These distributions correspond to different amounts of RBs (or REs) allocated to traffic signals within the part of the channel bandwidth demarcated by the configured RBW around SS_{REF}. By taking into account the difference in power between the SSB distribution and the dominant Gaussian of the traffic samples for all three components, a total difference in gain of 7.3 dB is obtained (corresponding to a factor $\alpha = 5.37$).

3) MAXIMUM ELECTRIC-FIELD STRENGTH

Based on an $E_{RE,SSB}$ of 0.067 V/m (Table 3) and a maximum channel occupancy of $N_{RB} = 106$, the theoretical maximum electric-field strength without taking into account a difference in gain between traffic and SSB signals in (1) would be 2.39 V/m (or 2.03 V/m when accounting for TDD) at Pos. 1. This value is actually lower than the maximum instantaneous field strength of 3.72 V/m measured at this position (Table 3). However, when applying $\alpha = 5.37$, experimentally derived based on the difference in power per 1 MHz (or 34 subcarriers in this case) between symbols allocated to SSB and to traffic (Fig. 7), in (1), we obtain 5.537 V/m (4.715 V/m with TDD).

V. DISCUSSION AND CONCLUSION

In this paper we introduced and tested on a 5G site for the first time a comprehensive methodology to assess *in-situ* the exposure to radiofrequency (RF) electromagnetic fields (EMFs) emitted by fifth generation New Radio (5G NR) base stations.

The proposed five-step measurement methodology consists of (1) a spectrum overview to identify the 5G NR channels; (2) the identification of the frequency position SS_{REF} of the synchronization signal block (SSB), which contains the 5G NR 'always-on' signals, as well as the subcarrier spacing (SCS) of the SSB, and the channel bandwidth of the signal under test); (3) the measurement of the electric-field strength per resource element (RE) of the SSB; (4) the measurement of the time-averaged instantaneous exposure level; and (5) the extrapolation of the electric-field strength per RE to the (theoretical) maximum electric-field level, based on a fully-occupied 5G NR channel, and, if known, the difference in gain between SSB and data traffic beams. Furthermore, to obtain the *actual* maximum exposure level, following IEC Standard 62232:2017 [17], additional factors such as a spatial duty cycle factor (for spatial multiplexing of MaMIMO), a temporal duty cycle factor (due to varying use of resources), and a TDD factor can be added to the theoretical maximum exposure level.

The procedure was validated in LOS of a 5G NR base station operating at 3.5 GHz in Düsseldorf, Germany. At the validation site, one user equipment (UE) was available with which various tests (100% downlink or uplink, voice call, video call, and video streaming) were performed. At a distance of 62–66 m from the base station radio, electric-field levels per RE of the SSB of 0.032–0.067 V/m were measured and extrapolated to a (conservative) theoretical maximum field strength of 5.537 V/m (4.715 V/m when accounting for TDD), while the time-averaged electric-field levels ranged between 0.288 V/m for a single UE scenario (video streaming) and 3.716 V/m for a 100% downlink scenario. All these values are well below the ICNIRP reference level of 61 V/m at 3.5 GHz [2].

Frequency-selective extrapolation was previously discussed by Keller [15], who stated two preconditions for it to work: (1) REs outside the SSB are not transmitted at higher power or antenna gain than the SSB REs, and (2) SSB REs are transmitted at a constant power and constant gain. While we agree with the second, the former is not a precondition for our proposed extrapolation method. To account for the difference in antenna gain between broadcast and traffic signals, we introduced the factor α in (1). Keller actually added a similar parameter in his extrapolation equation accounting for the transmission of REs outside the SSB at a different power (k_{system} [15]).

The assessed base station was not part of a commercial network and it was set to transmit with a fixed beam. Moreover, just one UE was available for tests. While this allowed to validate the proposed methodology in a well-controlled environment but for very different traffic scenarios, additional tests should nevertheless be carried out in a live network to generalize the methodology. For example, it is possible that the current method and SA settings for Step 2 (Table 2) are not adequate to identify the SS burst frequency position in the presence of traffic signals. It is also important to note that the extrapolation of $E_{RE,SSB}$ to the theoretical maximum electric-field level E_{max} of (1) assumes that traffic and broadcast beams are subject to the same propagation path.

In addition, although we were unable to perform tests with 5G NR signals at higher frequencies ('mmWaves'), the procedure should remain valid, providing that the measurement settings of Table 2 are adjusted to account for wider channel bandwidths as well as SCS of 120 kHz and 240 kHz.

Finally, since the focus of this paper was on the measurement of base station downlink exposure, uplink traffic contributions were unwanted. In the case of TDD, uplink traffic can contribute to the measured field levels using the SA method if a UE was in the vicinity of the measurement probe (such as at Pos. 2, Fig. 6). The influence of UE on the measurements and the distance beyond which uplink signals from UE do not impact the measurement results should be further evaluated in future work.

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