IN-SITU 5G NR BASE STATION EXPOSURE OF THE GENERAL PUBLIC: COMPARISON OF ASSESSMENT METHODS

Kenneth Deprez*, Leen Verloock*, Loek, Colussi, Sam Aerts*, Matthias Van den Bossche*, Jos Kamer**, John Bolte***, Luc Martens*, David Plets* and Wout Joseph***

(email: Kenneth.deprez@UGent.be)

***Department of Information Technology, Ghent University / IMEC**

Technologiepark-Zwijnaarde 126, B-9052 Ghent, Belgium

**** Radiocommunications Agency, The Netherlands**

*****National Institute for Public Health and the Environment, The Netherlands & Smart Sensor Systems research group, The Hague University of Applied Sciences, The Netherlands**

IN-SITU 5G NR BASE STATION EXPOSURE OF THE GENERAL PUBLIC: COMPARISON OF ASSESSMENT METHODS

Kenneth Deprez, Leen Verloock, Loek Colussi, Sam Aerts, Matthias Van den Bossche, Jos Kamer, John Bolte, Luc Martens, David Plets and Wout Joseph

Abstract- **New measurement methods and equipment for correct 5G New Radio (NR) electromagnetic field (EMF) in-situ exposure assessment of instantaneous time-averaged exposure (E_{avg}) and maximum extrapolated field exposure (E_{max}) are proposed. The different options are investigated with in-situ measurements around 5G NR base stations (FR1) in different countries. The maximum electric field values satisfy the ICNIRP 2020 limit (maximum 7.7%). The difference between E_{max} and E_{avg} is < 3 dB for the different measurement equipment at multiple sites in case there is only self-generated traffic. However, in a more realistic scenario, E_{avg} cannot be used to assess the exposure correctly due to influence of other users as the spatial distribution of user equipment (UE) influences E_{avg}, while E_{max} is not affected. However, when multiple UEs are collocated, there is no influence of the number of UEs. A broadband measurement can give a first impression of the RF-EMF exposure up to 700 m, but is not enough to assess the 5G-NR exposure.**

***Key Words*- 5G, 5G New Radio, electromagnetic fields, exposure assessment, Massive MIMO, measurement equipment, New Radio, RF measurement, RF-EMF**

INTRODUCTION

Nowadays 5G New Radio (5G NR) deployments are being rolled out. In many countries there are concerns about exposure caused by these new 5G NR roll-outs. 5G NR[1] is different from existing, well-known telecommunication signals used so far (i.e., 2G, 3G, and 4G). 5G NR makes extensive use of Massive MIMO (MaMIMO), introduced in 4G Long-Term Evolution (LTE) Advanced, which enables interactive directional narrow beam steering capabilities. Moreover, it uses a reduced amount of broadcast and control signals, which are transmitted independently of the active traffic load. Additional spectrum is used, new sub-6-GHz frequencies (e.g. 3.5 GHz band) and also mmWaves (above 24 GHz) are introduced with 5G NR to quickly transfer high amounts of data over larger bandwidths (up to 100 MHz for sub-6-GHz, 400 MHz for mmWaves). It is important to accurately assess the electromagnetic field (EMF) values from 5G NR base stations (BSs) in order to check compliance with international guidelines such as those of the International Commission on Non-ionising Radiation Protection (ICNIRP)[2] and the Institute of Electrical and Electronics Engineers (IEEE)[3]. Measurement methodologies used so far for current telecommunication signals are not applicable for 5G NR. 5G NR user-dependent narrow beams switch on and off depending on the activity of the user equipment (UE) and may also follow the user. Additionally, multiple constructively interfering beams can be used to enhance signal quality at the user location. This beamforming may lead to a decreased average field strength in public exposure, but also to an increased local variation and an increased exposure at the location of the user. Moreover, the exposure closer to the base station may be lower than at the location of the user. Therefore, new measurement methodologies have to be developed.

Research about measurement methodologies for 5G NR signals is ongoing, including simulations[4] and measurements[5-8]. In general, two different exposure metrics can be considered, (i) actual momentary or instantaneous time-averaged field levels on the one hand and (ii) extrapolated maximal field levels on the other hand. Current exposure assessment methods of 5G NR base stations can be found in the International Electrotechnical Commission (IEC) standard[9]. This standard describes different approaches: code-selective measurement equipment or spectral measurement equipment whether or not in combination with base station specific parameters.

The goal of this paper is to compare correct measurement procedures (including equipment and settings) for different in-situ 5G assessment methodologies around 5G NR base stations and apply these at various sites. Only downlink (DL) signals in the frequency band n77 (3300 to 4200 MHz) will be considered. Firstly, the exposure metrics will be proposed and discussed. Secondly, an overview of the available measurement equipment, their applicability and correct instrument settings for the different metrics will be presented. Finally, an overview and application of the methodologies for real in-situ 5G NR measurements performed in different countries will be discussed. Results will be shown in regard to the spatial distribution of User Equipment (UE) and number of UEs used. In addition, the position of the UE in regard to the measurement probe is investigated. The use of a broadband probe will be discussed to adequately assess 5G NR exposure.

This study will enable governments and researchers to perform 5G NR assessment in a correct way with various available equipment types. According to the 5G NR release[1], the 5G NR frequency range (FR) is split into two parts, the first frequency range from 410 MHz to 7.125 GHz (FR1, 'sub-6 GHz'), and the second from 24.25 GHz to 52.6 GHz (FR2, 'mmWaves'). Besides this, time-division duplexing (TDD) and frequency-division duplexing (FDD) can be used. The results, procedures, and methodologies of this paper can be used by authorities and epidemiologists to estimate the exposure from 5G NR.

MATERIALS AND METHODS

Overview of 5G NR measurement sites

Table 1 lists the investigated measurement sites per country. The center frequency (CF), bandwidth (BW), output power and height of the antenna is given. All BSs are sub 6 GHz macro cells. The measurement site in Switzerland is a commercial site (S1), although with limited active users; the other sites are test sites. The output powers of the Switzerland commercial measurement site is considerably lower (*8.1 W*) than the BS radio product's maximum input power of *200 W* due to the restrictive EMF limits applicable in Switzerland. The test sites vary in output powers from *6.4W to 160W,* thus also under the maximum input power of *200 W*. Furthermore, the Massive MIMO (MaMIMO) BSs were characterized by codebook-based beamforming configured with eight Channel State Information Reference Signal CSI- RS ports (with only azimuthal beam steering).

Exposure metrics

For comparison and compliance with the reference levels of the exposure guidelines[(2), (3)] one can consider for 5G NR systems (i) the time-averaged instantaneous, and (ii) the theoretical (extrapolated) maximum power density values (S [W/m^2]). The time-averaged values have to be measured and averaged over a certain time, i.e., 30 min for whole body-exposure[(2),(3)] and 6 min for local exposure[(2)]. Due to the variation of the traffic-load and the variation of the output power of the BS, the power density values vary over time: Aerts et al. [(10)] present a long-term analysis of electric-field levels for a GSM- and an UMTS network. The theoretical maximum power density values can be extrapolated based on these long-term measurements and additional information of the maximum realistic and theoretical output power of the BS. However, for MaMIMO, as used for 5G NR FR1, these maximum values are very conservative and give a worst-case unrealistic overestimation of the exposure levels for 5G NR systems[(5),(9),(11),(12)]. The extrapolation assumes a fully occupied channel, which is continually transmitting at the highest power and gain with a beam continuously directed towards the evaluation location. In reality, this is highly unlikely due to the dynamically adjustable narrow beams towards the different users. Either swapping from one user to another or concurrently transmitting to all users with the power distributed over the UEs. This time-averaged spatial distribution of the transmitted BS power requires an additional approach for compliance evaluation by introducing additional factors (such as the spatial distribution of the beams during a certain time) to estimate the actual maximum power density. Thors et al. [(5)] and the IEC [(9)] provide further information about the assessment of the actual maximum exposure. Consequently, long-term measurements, simulations and the application of statistical techniques will be required to assess the realistic maximum averaged exposure. To evaluate the evolution over time, a monitoring network[(13)], with low-cost RF-sensors capable to measure frequency bands in use by 5G signals[(14)] can be used.

In this paper practical measurement methodologies in real 5G NR commercial or test networks will be described using measurement data of four countries: Belgium, The Netherlands, Switzerland and Germany. Different options for practical EMF assessment as proposed by Aerts et al. [(7)] and the IEC [(9)] are shortly described below.

Instantaneous exposure evaluation

The time-averaged instantaneous exposure level (E_{avg}) is measured over the entire 5G NR signal channel bandwidth using a root mean square (RMS) detector during a time in accordance with the averaging time of the considered exposure limits (e.g. 6 minutes for local exposure[(2)] and 30 minutes for whole body exposure[(2),(3)]). In practice a shorter averaging time is sufficient to derive a field-value representative of longer averaging times[(15),(16)]. For the settings of the measurement device, limited knowledge of the 5G NR base station specifications is required. Only the frequency and bandwidth of the considered 5G NR signal are needed besides correct signal-specific settings[(17)]. During the measurements, the personal UEs of the measurement operator and bystanders are disabled to avoid interference during the measurements. By extension also a long-term measurement of the instantaneous field levels during longer periods (e.g., 24 hours, one week) can be performed to determine the level of variation over time and to calculate realistic maximum and median time-averaged values[(10),(18)].

Additional instantaneous average field measurements have to be performed with an active test UE (i.e., traffic mode) to evaluate the influence of attracting the 5G NR beam towards the UE and thus the measurement probe. Due to the dynamic beam steering and placing the measurement probe in Line Of Sight (LOS), the maximum exposure values will occur near the UE. During these measurements, the contributions from uplink (UL) signals must be limited, especially for TDD systems. This can be done by using for example a download protocol with minimal uplink activity (e.g., User Datagram Protocol (UDP)) or by defining a minimal distance between the measurement probe and the UE so that the contribution of UL signals can be neglected, which is particularly important when omnidirectional antennas are used.

Several configurations were tested e.g., a downlink file transfer using different file sizes, a network performance tool (e.g., the iPerf tool https://iperf.fr/), or other freely available, internet-based network performance test applications (e.g. Ookla Speedtest). Measurements with file transfers of different sizes averaged over a continuous time duration (e.g., 6 minutes for localized exposure according to ICNIRP) quantifies the EMF exposure as a function of the file size and the download time at the assessment location, which depends on the network quality. Common user scenarios for the active UE such as a video call, a voice call, a livestream TV emulate more realistic usage scenarios(7). The data rate and the occupation of resources over the channel bandwidth during time depend on the number of connected active users and on the network quality. These parameters influence in turn the streaming time and thus the averaged EMF exposure levels.

Maximum exposure evaluation

Comparable to the older telecommunications signals, the assessment of the maximum exposure of 5G NR signals is based on the measurement of a time-invariant signal component that is transmitted periodically at constant power, independent of the traffic load and user behavior(7),(9),(11),(12),(19). In (9), worst-case extrapolation using the synchronization signal/physical broadcast channel (SS/PBCH) signal level (i.e. Synchronization Signal Block (SSB)) or the channel state information reference signal (CSI-RS) level, in combination with additional BS-dependent knowledge (e.g. the maximum gain of traffic and broadcast beams at the measurement point), is discussed. One has to remark that for the SSB extrapolation method, no special configuration of the BS is required because this control signal is always present, while the CSI-RS method is only applicable when a special configuration mode is enabled in the BS by transmitting a channel-width CSI-RS signal at a constant gain difference between the traffic beam envelope and the CSI-RS beam. So a measurement of the signal per resource element (RE) in combination with the knowledge (based on simulations or provided by the network operator or derived from the analysis of specific measurements) of additional parameters (e.g. the signal bandwidth, the gain difference between the user data and the measured reference signal level) can be used to calculate the theoretical maximum worst-case exposure (E_{max})[7]. These additional parameters can be requested from the operator or obtained from simulations or specific additional measurements. E_{max} is then calculated as follows:

$$E_{max} = E_x \sqrt{F_{BW} \frac{G_{max}}{G_{SSBorCSI-RS}}} \qquad (1)$$

with

x	the dominant SSB or CSI-RS,
E_x	the measured electric-field level per RE of the dominant SSB of the SS burst (multiple SSBs combined to form a SS burst) or the electric-field level of the CSI-RS signal, both in the direction of the measurement location,
F_{BW}	the total number of subcarriers within the 5G NR channel bandwidth,
G_{max}	the maximum gain in the direction of the measurement location,
$G_{SSB\ or\ \mathrm{CSI\text{-}RS}}$	the gain of the dominant SSB or the gain of the CSI-RS in the direction of the measurement location.

This theoretical maximum worst-case exposure assumes that the BS is continuously transmitting a fully occupied 5G NR frame (100% DL slot occupation) at the highest gain in the direction of the measurement location. As already stated above a more realistic approach for the maximum exposure evaluation is the actual maximum exposure ($E_{max,actual}$) taking into account additional parameters such as the downlink duty cycle (for TDD systems), the spatial distribution of energy (i.e., distribution of energy over different beams) during the measurement time, and the activity factor of the BS resources [(5),(7),(9),(19)].

Alternatively, a more practical approach for in-situ measurements to assess $E_{max,actual}$ experimentally is an instantaneous electric-field measurement using an active UE with a 100% downlink (DL) data stream. One has to remark that all DL resources over the whole channel bandwidth must be occupied continuously (or at least a fixed part of the channel) and that the uplink stream must be distinguishable. Here, power control must be taken into account as well if present. As discussed further, this will be only usable for networks with no or very limited data traffic from other users.

Measurement equipment and usability for the assessment 5G NR signals

In-situ measurement equipment for electromagnetic field measurements of telecommunication signals consists of a measurement probe connected to a measurement receiver. Some probes are part of a complete commercial measurement system (e.g., probes for broadband measurement systems[(20)]). The frequency ranges of the probe and the measurement receiver define the bandwidth of the measurement system. For in-situ measurements around RF base stations, electric-field measurement systems are available. The power density value (*S, W/m^2*) can be derived from the electric field value (*E, V/m*) in the far field. In the following, we will discuss (i) measurement antennas, (ii) measurement receivers (broadband, narrowband, spectrum analyzer, decoder) and (iii) UE, all required for 5G NR exposure assessment. However, each measurement setup has a certain uncertainty, which can affect the exposure assessment. The measurement uncertainty (expanded uncertainty with a confidence interval of 95%) was estimated to be ± 3 dB [21]. This uncertainty is invoked by the calibration of the antenna and the measurement receiver.

Measurement antennas

For in-situ measurements, isotropic probes are required (to measure radiation from all directions around the measurement probe). For sub-6GHz 5G NR measurements, the antennas used are selected so that the antenna setup has an omnidirectional antenna pattern. The total electric field is measured by rotating the antenna in the three orthogonal directions or by switching sequentially to three internal orthogonally placed axial antennas inside the antenna system (also called a tri-axial antenna).

However for mm-waves, horn antennas are mostly used. These antennas are directional with a small aperture. For a 360° coverage over one axis, the horn antenna must be rotated sequentially or a circular array of multiple horn antennas controlled by a fast mm-wave switch can be used (e.g. Keysight 5G Network Mobile Field testing[22]). The number of antennas or the step to cover the 360° sector depends on the beam width of the directional antenna. Besides these directional antennas, there are also omnidirectional antennas available in different mm-wave frequency bands. Depending on the frequency, the size of these omnidirectional antennas varies between 101 mm (18-23 GHz) to 40 mm (50-75 GHz) in diameter. The advantage of an omnidirectional antenna compared to an array of antennas is the simultaneous measurement in all directions along one axis. A disadvantage is the antenna gain of a horn antenna, which is important at these high frequencies.

Measurement receivers

Two types of measurement receivers are available i.e., broadband and narrowband (also denoted as frequency-selective) measurement systems, whether or not connected to external control equipment (e.g., a laptop).

1. *Broadband meter*

Broadband meters are easy-to-use, compact systems that give an initial idea of the cumulative instantaneous time-averaged field-value over the frequency range of the connected probe[23]. The disadvantage of these systems is that no frequency-selective information is available. No distinction between 5G NR signals and other present signals can be made in-situ where the present signals cannot be switched off. However, due to the user-directed beamforming in 5G, the broadband setup can be used for measurements of the actual maximum field values using an active UE (100% DL 5G activity) if it dominates the 'background' measurement without active UE.

2. *Frequency-selective or narrowband receivers*

Frequency-selective receivers can be used to accurately measure at a specific frequency. Moreover, these receivers are more sensitive and thus more accurate than broadband measurement systems. The main disadvantage is that these instruments are more complex to use and have a multitude of settings to optimize and tune. Specifically for 5G NR signals, a spectrum analyzer (conventional and real-time), a 5G decoder and a real-time analyzer are considered here.

Spectrum analyzer (frequency-selective)

Aerts et al. [7] presented a complete measurement methodology (a five step procedure), including time-averaged and maximum field measurements for 5G NR base stations using a conventional spectrum analyzer. Some parts are adopted by the IEC [9]. For accurate measurements, the required analyzer settings (e.g. sweep time, resolution bandwidth) as presented in [7] must be met. For the estimation of the maximum-field level based on the SS/PBCH a spectrogram mode is required, while the time-gating functionality of the SA is proposed for the measurements based on the CSI-RS[9]. A disadvantage of a spectrum analyzer is that no distinction between the broadcast signals of different BSs can be made without demodulation and decoding the 5G NR signal.

A real-time spectrum analyzer (RTSA) can be used as an alternative to a normal spectrum analyzer to visualize and analyze the 5G NR frame as function of the time. While a normal SA uses a sweep-based filter (Fast Fourier Transform (FFT) or super heterodyne receiver) with a limited resolution bandwidth (often up to 20 MHz), an RTSA uses real-time acquisition over a large signal bandwidth (e.g. defined by the sampling rate of the FFT), incorporating the maximum 5G NR channel bandwidth of 400 MHz. Consequently, an RTSA can record, analyze, and reproduce the 5G NR signal across the whole available instantaneous bandwidth (e.g. 40 MHz). Post-processing of RTSA data facilitates and automates the process of extrapolation. One has to remark that high-frequency broadband RTSA equipment is mostly very expensive lab-equipment and not practically usable for in-situ measurements.

5G NR decoder (code-selective)

With a 5G NR decoder, the field value per RE of the secondary Synchronization Signal (SSS) part of the SS/PBCH block can be determined for each present broadcast beam in order to calculate the maximum field strength. Because the measured signal is demodulated and decoded, the corresponding cell IDs of the 5G NR base stations and beam IDs of the SSB are also available. This makes it possible to identify the different base stations contributing to the total measured field at the measurement location, which is not possible with the spectrum output from a spectrum analyzer. There are different types of 5G NR decoders available such as expensive lab equipment (e.g. real-time vector signal analyzers in combination with specific 5G NR demodulation software), more compact battery powered systems for in-situ measurements (e.g. Fieldfox from Keysight, SRM3006 from Narda, Field Master from Anritsu) and field drive tests (e.g. Nemo system from Keysight, Romes from Rohde&Schwarz).

Also other IQ streaming devices (e.g. low- cost RSA306B RTSA from Tektronix) in combination with demodulating and decoding software can be used to retrieve the field-strength per RE of the present SSS for each detected 5G cell. One has to remark that for these devices additional third party or own implementations are required.

User device

To attract the 5G NR signal towards the measurement probe, an active UE is used. To connect and establish a DL data connection with the different present UE, 5G NR operators provide a SIM-card with unlimited data volume as a continuous download is required (e.g., a data download of 600 Mbps during 6 minutes gives a data volume of 27 GB).

To set up a DL communication, tools such as iPerf3 or downlink speed tests are used. The main disadvantage of such in-situ DL tests is the influence by other active 5G NR users or possible power control, resulting in a possible underestimation of the maximum field values. Additional analysis tools or cooperation of the telecom operator for detailed information about the resource allocation of the 5G NR channel frame over time during the measurements can be considered. Dedicated smartphone applications (e.g. Qualipoc Android from Rohde & Schwarz, Nemo Handy from Keysight) to setup a lot of different tests (streaming, voice call, etc.) while continuously logging parameters such as the received power, the DL speed, the resource allocation are also relevant in this context.

RESULTS AND DISCUSSION

Assessment of the maximum electric-field strength using different measurement equipment

The measurement equipment consists of a measurement probe connected to a measurement receiver (Section Materials and Methods). Table 2 provides an overview of the electric field values measured with different measurement equipment at the measurement sites of Table 1, with settings and powers indicated. As the investigated sites were either test sites or commercial sites with limited traffic, traffic mode (i.e., generate downlink exposure) is tested with one UE or multiple UEs continuously downloading. No scaling of the measurement results regarding different output powers of the BSs has been performed. Table 2 shows field values ranging from 0.4 V/m to 4.9 V/m with an active UE and 0.05 V/m to 0.18 V/m without an active UE. The distance to the base station ranges from 62 m to 300 m.

The equipment used to assess the exposure is summarized in Table 3. For the "worst-case" exposure (i.e. E_{max}), a (real-time) spectrum analyzer (i.e., Rohde & Schwarz (R&S) FSV-30 with option R&S FSV-K14 spectrogram, SRM3006 from Narda, or Tektronix RSA306B) or a 5G NR decoder (R&S TSME scanner with Romes demodulation software) were used. The FSV was used on sites B1, B2, G1 and S1 while a decoder was only used for site G1. On sites N1 and N2, the RSA306B was used to determine E_{max}. The time-averaged instantaneous exposure level (E_{avg}) was also be assessed by means of a (real-time) spectrum analyzer (i.e., Rohde & Schwarz (R&S) FSV-30 with option R&S FSV-K14 spectrogram, SRM3006 from Narda, or Tektronix RSA306B). The SRM3006, FSV and TSME scanner were all connected to an omnidirectional probe, the RSA306B was connected to a directional horn antenna.

The procedure to determine E_{max} and E_{avg} with a FSV can be found in Aerts et al. [7] and equal to "Step 3" and "Step 4" (Section Materials and Methods), respectively. To determine E_{max} and E_{avg} with the RSA306B, a different approach is used. The RSA306B captured a 100 milliseconds long signal over the full bandwidth of the device (i.e., 40MHz). If the BW of the 5G channel is larger than the BW of the device, the obtained result was extrapolated to match the bandwidth of the 5G channel. E_{max} was defined as the maximum averaged over one Orthogonal frequency division multiplexing (OFDM) symbol, to counter variations within an OFDM symbol. E_{avg} was defined as the average over the entire measurement (i.e., 100 ms), on the assumption that the signal was stable. At site G1, the FSV was validated by using the 5G NR decoder at several measurement spots. Table 2 shows the maximum observed exposure for the devices differs 0.97 dB, which is within the uncertainty limit of the measurement equipment. Hence, it can be concluded that an FSV can be used to correctly assess 5G exposure and no 5G demodulation software is needed.

Due to the current lack of traffic, E_{max} can be compared to the time-averaged instantaneous exposure level (E_{avg}) to compare both assessment methods. Therefore, the different measurement equipment can be compared and conclusions can be drawn to the usability of the measurement equipment. First, a comparison is made when there is 100% downlink traffic induced. For all sites, an average difference of 1.06 dB was found between E_{max} and E_{avg}, with a maximum of 1.58 dB at N2. The same comparison was made between E_{max} and $E_{avg,SRM}$ and E_{avg} and $E_{avg,SRM}$. Averages of 1.65 dB and 1.04 dB were found respectively. Thus there was a good agreement in assessing E_{max} and E_{avg} when there was no (or limited) traffic of other users and with maximum downlink towards the measurement location, regardless the measurement equipment.

Second, when no active UE was present, E_{avg} and $E_{avg,SRM}$ have a difference of 11.13 dB for site S1. This can be explained by the sensitivity of the measurement equipment. The FSV is highly tunable, which leads to a lower noise floor and thus less attribution of noise.

In conclusion, all of the proposed measurement equipment can be used to assess electric-field values in situ in the current scenario, i.e., one dominant beam attracted by the active UE.

The maximum electric field value (as obtained in G1) is still only a fraction (i.e. 7.7%) of the ICNIRP 2020 limit (61 V/m) at 3.5 GHz [(2)].

As mentioned before, the different measurement equipment is summarized in Table 3. A real-time spectrum analyzer (such as the RSA306B), is a highly portable and affordable package which is ideal for field use. A software package (e.g. Matlab) to correctly assess the field radiation must be bought or made in-house, as there is no visualization on the device itself. The drawback of this device is the limited bandwidth of 40 MHz, which is too narrow to capture the full bandwidth (up to 100MHz for sub 6GHz). However, if the full bandwidth can be measured, automatic SSB detection is possible. Otherwise, the SSB frequency must be entered manually. The main advantage of using the FSV is the high flexibility in settings, tailoring the settings to an individual setup. The high flexibility is coupled with a high accuracy. The results, however, also must be processed through bought or made software and due to the high complexity of the device, the device is less accessible. The main advantages of the SRM3006 are the portability and price. However, the SRM3006's parameters are less adjustable. The main advantage of using a decoder finally is that the ID of the broadcast beam can be determined and thus the contribution to the total exposure per BS. In future environments, more than one BS could be connected to the UE, so the decoder can help the operator to correctly assess 5G-NR exposure.

Influence of the number of active UEs and the beam separation of the UEs

Multiple UEs in same beam

To assess the exposure originating from the BS, the beam is "attracted" to the measurement probe. Due to the limited traffic in the 5G telecom band at this time, this method is valid to measure E_{max} when one or multiple UEs are active in the same beam. To assess this, up to four simultaneously active UEs were placed at 3m behind the measurement probe in LOS of the BS. E_{avg} ranges from $1.80\ \frac{V}{m}\ to\ 1.87\ \frac{V}{m}$ (Figure 1); as such, there was no apparent influence of the number of concurrently active UEs on the exposure. Therefore, to determine the exposure in a low-traffic environment, one test UE suffices for assessing the exposure of the BS as the downlink channel was already maximized.

Multiple UEs in different beam

However, in the future, the network will be used actively by many users scattered over the environment, attracting in *different* beams. Therefore, the effect of multiple UEs in different beams was investigated. Up to four simultaneously active UEs were placed in the antenna sector at spatially uncorrelated such that they were assumed to be served by different Physical Downlink Shared Channel (PDSCH) beams (i.e. they were spatially separated). E_{avg} in these scenarios is shown in Figure 2. Comparing the measurements with the theory, E_{avg} decreases as expected (within the ±*3 dB* measurement uncertainty – green area in Figure 2), starting from the average exposure level measured with one active UE near the measurement probe ($1.74\ \frac{V}{m}$), where one PDSCH beam is directed towards the probe. For two active spatially separated UEs – which means the antenna power was split over two PDSH beams – E_{avg} was 2.3 dB lower (close to the expected 3dB, which corresponds to a factor 2 in power density or $\sqrt{2}$ in electric field strength). For three UEs, E_{avg} was 2.6 dB lower. Theoretically, 4.6 dB was expected but E_{avg} agrees well with deviations within the measurement uncertainty. The overestimation is probably due to a small but measurable contribution of the beams to the electric field at the measurement position, due to the side lobes of the antenna pattern. Finally, for four UEs, E_{avg} was 5.4 dB lower, close to the expected 6 dB i.e., a factor 2 in electric field strength.

It can thus be concluded that the field value decreases if other UEs are (100%) active in different beams. As a result, worst-case electric-field values cannot be measured accurately with the averaging method (as used in SRM, RSA306B and Step 4 method) using 100% DL UE in a heavytraffic network. However, Step 3 is unaffected by multiple UEs in different beams (i.e., 2.40 V/m, 2.24 V/m, 2.40 V/m and 2.29 V/m, respectively). There is only a variation of 0.60 dB between the various measurements and it can thus be used to correctly assess the maximum "worst-case" exposure in all environments. Even in future dynamic environments, where users (i.e. UEs) require high rate beam switching, the Step 3 method can still accurately assess E_{max} as the method is unaffected by other users nearby.

Influence of the position of the UE around the measurement probe

Distance between active UE and measurement probe to avoid uplink signals in results

At the frequency of interest (band n78 in 5G NR; 3300MHz – 3800 MHz), TDD (time-division duplexing) is used. As the exposure of interest is originating from a BS, a minimum distance must be kept between an active UE and the measurement probe to avoid influence of UL signals in the results if no distinction can be made between DL and UL signals. Therefore, in the proposed step 3 (Section Materials and Methods) a waterfall diagram is made to visualize a 5G frame (Figure 3). To align the measurement data, the four-symbol-long SSB is identified and located in subframe 0 of the waterfall model[7]. Here, a DDDSU (with D: Downlink, S: Special slot; can contain either downlink or uplink, and U: uplink) pattern can be distinguished, with the power of UL slots equal or lower than the noise floor.

Position of the UE with respect to the measurement probe

With the measurement probe fixed at a random position LOS of the 5G NR BS, the UE was placed at eight different positions around it: in front of it (i.e., towards the BS), on the left and on the right of it, and behind it, and at a separation distance of either 2 m or 3 m. The average electric-field strengths E_{avg} measured in these scenarios are visualized in Figure 4. Although E_{avg} with the UE on the side were slightly lower, all measurements were well within 3 dB of $\overline{E_{avg}}$, so the eight positions of the UE did not influence the measurements above the uncertainty of the setup. To avoid high received powers in UL slots, a minimum distance of 2 meter between the UE and the probe is proposed, with the UE in front of the probe (i.e. towards the BS). In certain situations it is infeasible to place the UE two meter in front (i.e. towards the BS) of the probe, however it has been proven that the UE can placed around the probe without altering the assessed exposure.

Broadband measurements versus frequency-selective measurements

During measurements, a broadband probe can be used to give a first impression of the RF-EMF exposure assessment. Furthermore, a broadband probe can be used to determine the optimal location to place a narrowband measurement device, i.e. either SRM or SA. For this research, a Narda NBM 550 broadband probe was used. There are two measurement types to be performed with the broadband probe: first without an active 5G-NR UE and second with an active UE close by the broadband probe as to ensure that both UE and probe are in the same beam. The following considerations are made: the broadband probe is held at 1.5 m above street level to equal other measurements; the 5G-NR device is active (i.e. downloading) in the 5G-NR band; the distance between the UE and probe is large enough to minimize the influence of uplink signals and close enough to ensure that the probe and UE are in the same beam (2-3m as above). If the probe is stationary and both tests have been performed, a raw assessment of the 5G-NR BS exposure can be made. Figure 5 shows the broadband versus narrowband measurements. It must be noted that for the narrowband measurements, the cumulative exposure is shown (i.e. the contribution of all measured telecom signals to mimic a broadband measurement). Measurements have been performed at various distances (starting from 58 m to 918 m) from the BS, either LOS or NLOS.

When 100% downlink was generated by the BS, the broadband probe assessed the BS exposure accurately up until 700 meter separation as 5G NR was the dominating telecom technology; 0.05 to 4.86 dB (1.25 dB average) variation between broadband NBM 550 and narrowband SRM-3006 measurement. When the distance further increased, the broadband assessment differs to maximum 21.15 dB with respect to the narrowband SRM. The higher assessment can most likely be attributed to measuring of the UL signal of the UE. In case there is no active UE, the variation in exposure assessment between the broadband and SRM is 0.14 dB to 12.28 dB with an average variation of 2.63 dB. It can be deduced that the broadband gives a first indication of 5G exposure, for both with and without an active UE. However, a more detailed measurement is advised to accurately assess the 5G NR exposure.

CONCLUSIONS AND FUTURE WORK

This paper provides an overview of different measurement equipment and optimal settings that can be used to correctly perform in-situ 5G NR electromagnetic field exposure assessment at *3.5 GHz* (FR1). Both time-averaged exposure and maximum extrapolated field exposure assessment are proposed and investigated with in-situ measurements in different countries. The maximum electric field values satisfy the ICNIRP 2020 limit (i.e. maximum 7.7%). Furthermore, in a low-traffic environment, one UE is sufficient to attract the beam towards the measurement equipment. The difference between E_{max} and E_{avg} is < 3 *dB* for the different measurement equipment at multiple sites. Hence, the current setups are to be recommended in 5G-NR exposure assessment in the current low-traffic scenarios. In a more realistic scenario, not all measurement methods are valid and must thus be adapted. When E_{avg} is used as metric, the exposure assessment drops with *6 dB* when four UEs are spatially separated. However, E_{max} is not affected by the spatially separated UEs (difference of *0.60 dB* between the various measurements) and is the recommended metric to use for exposure assessment in high-traffic environments.

A broadband measurement can give a first impression of the RF-EMF environment up to 700 m (deviations of *0.05 dB* to *4.86 dB*), but is limited in use (larger separations) and not enough to assess the 5G-NR field exposure.

The future work can be divided into two main parts. The first part is to test the measurement methods and equipment in more realistic, higher traffic environments. This will give a more accurate view on the impact of 5G NR on everyday RF-EMF exposure. The second part is to test the measurement methods for the *frequency range 2* of 5G-NR (FR2), i.e. mm-waves. Here, more beams, higher bandwidths and more traffic are expected.

Acknowledgements

Sam Aerts is a postdoctoral fellow with the Special Research Fund (BOF).

REFERENCES

1. 3rd Generation Partnership Project (3GPP). Technical Specifications (TS) series 38. [online available: https://www.3gpp.org/DynaReport/38-series.htm].
2. International Commission on Non-ionizing Radiation Protection (ICNIRP). 2020. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Phys 118(00):000–000; (2020). Pre-print. DOI: 10.1097/HP.0000000000001210 https://www.icnirp.org/en/activities/news/news-article/rf-guidelines-2020-published.html.

3. IEEE C95.1-2019, IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz (2019) https://standards.ieee.org/standard/C95_1-2019.html.
4. Shikhantsov, S., Thielens, A., Aerts, S., Verloock, L., Torfs, G., Martens, L., … Joseph, W. (2020). Ray-tracing-based numerical assessment of the spatiotemporal duty cycle of 5G massive MIMO in an outdoor urban environment. APPLIED SCIENCES-BASEL, 10(21). https://doi.org/10.3390/app10217631
5. Thors, B, Furuskär, A, Colombi, D, and Törnevik, C. 2017. Time-averaged realistic maximum power levels for the assessment of radio frequency exposure for 5G radio base stations using Massive MIMO. IEEE Access, vol.5, pp. 19711-19719 (2017).
6. Shikhantsov, S., Guevara, A., Thielens, A., Vermeeren, G., Demeester, P., Martens, L., … Joseph, W. (2021). Spatial correlation in indoor massive MIMO : measurements and ray tracing. IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, 20(6), 903–907. https://doi.org/10.1109/LAWP.2021.3066607
7. Aerts, S, Verloock, L, Van den Bossche, M, Colombi, D, Martens, L, Törnevik, C, and Joseph, W. 2019. In-situ measurement methodology for the assessment of 5G NR massive MIMO base station exposure at sub-6 GHz frequencies. IEEE Access, vol7, pp. 184658-184667 (2019).
8. Aerts, S., Deprez, K., Colombi, D., Van den Bossche, M., Verloock, L., Martens, L., Törnevik, C., Joseph, W. In Situ Assessment of 5G NR Massive MIMO Base Station Exposure in a Commercial Network in Bern, Switzerland. Appl. Sci. 2021, 11, 3592. https://doi.org/10.3390/app11083592

9. International Electrotechnical Commission (IEC). Determination of RF field strength and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure IEC 62232, revision of IEC 62632:2017 – under revision (2020).

10. Aerts, S, Wiart, J, Martens, L, and Joseph, W. Assessment of long-term spatio-temporal radiofrequency electromagnetic field exposure. Environ Res. 161:136-143 (2018). doi: 10.1016/j.envres.2017.11.003. PMID: 29145005.

11. Keller, H. 2019. On the assessment of human exposure to electromagnetic fields transmitted by 5G NR base stations. Health Physics (2019).

12. Adda, A, Aureli, T, D'Elia, S, Franci, D, Grillo, E, Migliore, M, Pavoncello, S, Schettino, F, and Suman, R. A Theoretical and Experimental Investigation on the Measurement of the Electromagnetic Field Level Radiated by 5G Base Stations. IEEE Access (2020) doi: 10.1109/ACCESS.2020.2998448.

13. Vermeeren, G., Van den Bossche, M., Aminzadeh, R., Aerts, S., Leroux, P., De Meyer, M., Joseph, W. RF EMF exposure sensing network in a smart-city context. In *Proceedings of the Joint Annual Meeting of the Bioelectromagnetics Society and the European BioElectromagnetics Association (BioEM2019)* (pp. 239–243). Montpellier, France: Bioelectromagnetics Society (BEMS).

14. Deprez, K., Aerts, S., Thielens, A., Vermeeren, G., Martens, L., Joseph, W. Design of a low-cost modular 5G RF-EMF exposure sensor. BioEM2021, Ghent, Belgium, Sep 26 - Oct 01, 2021.

15. Verloock, L, Joseph, W, Vermeeren, G, and Martens, L. 2010. Procedure for assessment of general public exposure from WLAN in offices and in wireless sensor network testbed. Health Phys., vol. 98, pp. 628-638, no. 4 (2010).

16. ITU-T K.91, Guidance for assessment, evaluation and monitoring of human exposure to radiofrequency electromagnetic fields, document Rec. ITI-T K.91, (2018). [Online]. Available: https://www.itu.int/rec/T-REC-K.91-202012-I/en.

17. Joseph, W, Verloock, L, Goeminne, F. Vermeeren, G., and Martens, L., Assessment of RF exposures from emerging wireless communication technologies in different environments. Health Physics, vol. 102, no. 2, pp. 161-172 (2012).

18. Joseph, W, Verloock, L, Tanghe, E, and Martens, L. 2009. In-situ measurement procedures for temporal RF electromagnetic field exposure of the general public. Health Phys; vol. 96, pp. 529-542 (2009).

19. Pawlek, R, Krawiec, P, and Zurek, J. On measuring electromagnetic fields in 5G technology. IEEE Access, vol. 7, pp. 29826-29835 (2019).

20. Shalaby, M, Shokair, M, and Messiha, N.W. 2019. Electromagnetic Field Measurement Instruments: Survey. Iran J Sci Technol Trans Electr Eng 43, 1–14 (2019).

21. A. Hirata et al., "Assessment of Human Exposure to Electromagnetic Fields: Review and Future Directions," in IEEE Transactions on Electromagnetic Compatibility, vol. 63, no. 5, pp. 1619-1630, Oct. 2021, doi: 10.1109/TEMC.2021.3109249.

22. Keysight, 5G Network Mobile Field Testing, Keysight Technologies and TA Engineering, Inc. Online. Retrieved 4 June 2021 from https://www.keysight.com/us/en/assets/7018-06160/brochures/5992-2965.pdf.

23. Verloock, L, Joseph, W, Goeminne, F, Martens, L, Verlaek, M, and Constandt, K. 2014. Assessment of radio frequency exposures in schools, homes, and public places in Belgium. Health Phys., vol. 107 pp. 503-513 (2014).

List of captions

Figure 1: *Difference in average electric-field strength* E_{avg} *(V/m) at a fixed location (X) when zero to four simultaneously active UEs were placed at a fixed position in the antenna sector. The red markers depict the average* E_{avg} *measured for that number of active UEs.*

Figure 2: Average *electric-field strength* E_{avg} *(V/m) at a fixed location (X) when zero to four simultaneously active UEs were placed at different positions in the antenna sector, generating spatially separated PDSCH beams. The red markers depict the average* E_{avg} *measured for that number of active PDSCH beams. The dashed line indicates the theoretical decrease in* E_{avg}*, starting from the average* E_{avg} *measured with one PDSCH beam directed towards the measurement probe and the average of those was retained [red marker]). In green, the measurement uncertainty of ±3 dB is shown.*

Figure 3: Waterfall diagram to visualize the periodicity of the signals transmitted by a 5G NR base station.

Figure 4: Average electric-field strength E_{avg} (V/m) at a fixed location (x) when the UE was positioned at either 2 m (red) or 3 m (blue) from the measurement probe (at x) in four directions: in front of (i.e., towards the BS), left of, right of, or behind the measurement probe. The purple area (i.e., the overlap) indicates the smaller of the two values. The average of the eight measurements is indicated with a black line, and the ±3 dB deviations (i.e., the measurement uncertainty) from this average with dotted lines.

Figure 5: Measurement results with broadband and narrowband measurement system, organized by distance to the 5G base station. No differentiation is made between LOS or NLOS

Table 1: Overview of 5G NR measurement sites.

Table 2: *Measurement data of electric-field values measured with different measurement equipment around 5G NR BS in Belgium, The Netherlands, Germany and Switzerland.*

Table 3: Spectrum analyzer settings for sub-6GHz 5G NR signals

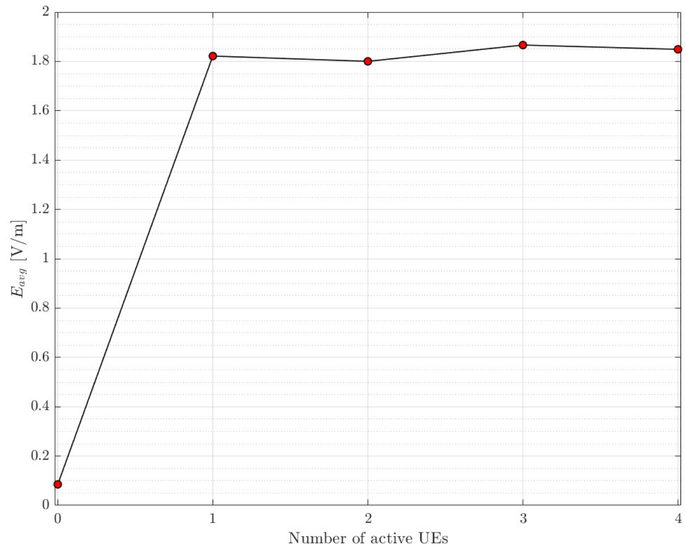

Figure 1: *Difference in average electric-field strength E_{avg} (V/m) at a fixed location (X) when zero to four simultaneously active UEs were placed at a fixed position in the antenna sector. The red markers depict the average E_{avg} measured for that number of active UEs.*

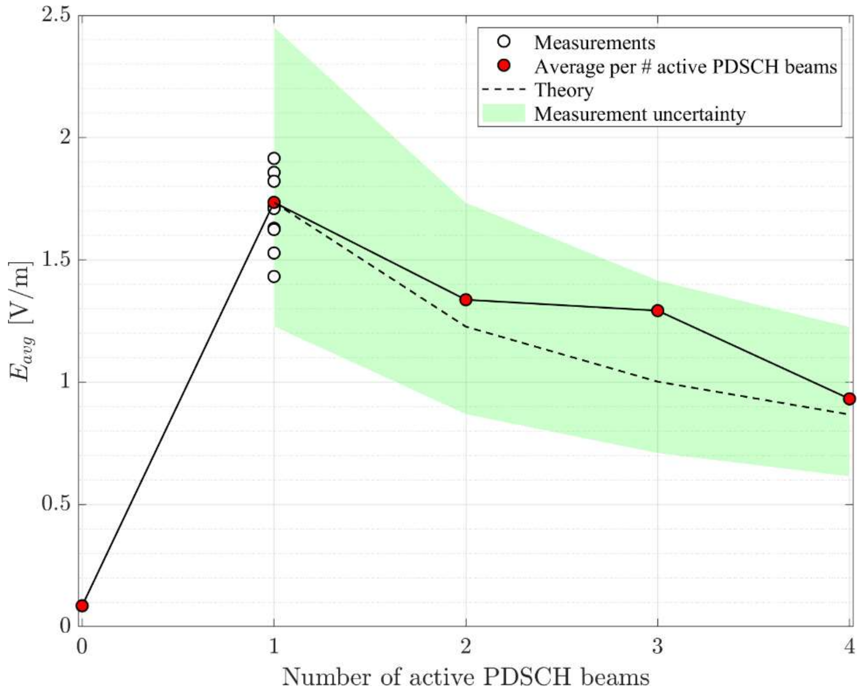

Figure 2: Average *electric-field strength E_{avg} (V/m) at a fixed location (X) when zero to four simultaneously active UEs were placed at different positions in the antenna sector, generating spatially separated PDSCH beams. The red markers depict the average E_{avg} measured for that number of active PDSCH beams. The dashed line indicates the theoretical decrease in E_{avg}, starting from the average E_{avg} measured with one PDSCH beam directed towards the measurement probe and the average of those was retained [red marker]). In green, the measurement uncertainty of ±3 dB is shown.*

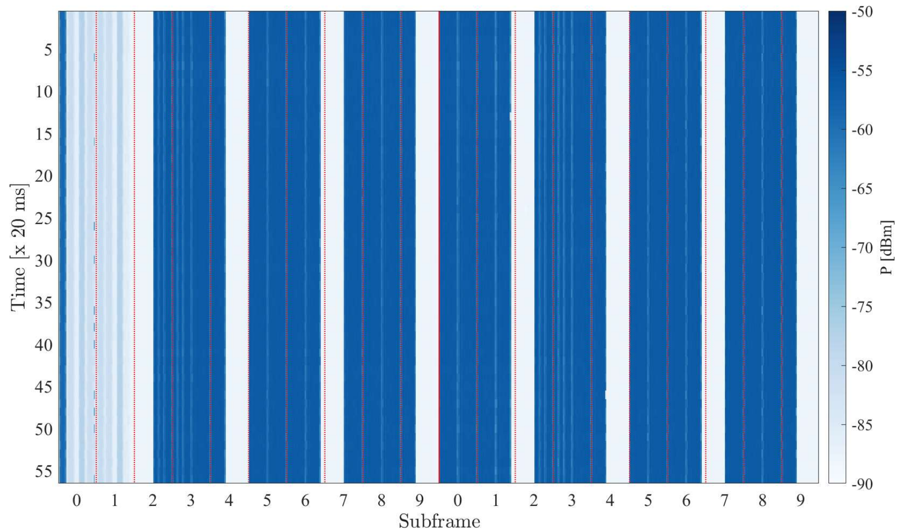

Figure 3: Waterfall diagram to visualize the periodicity of the signals transmitted by a 5G NR base station.

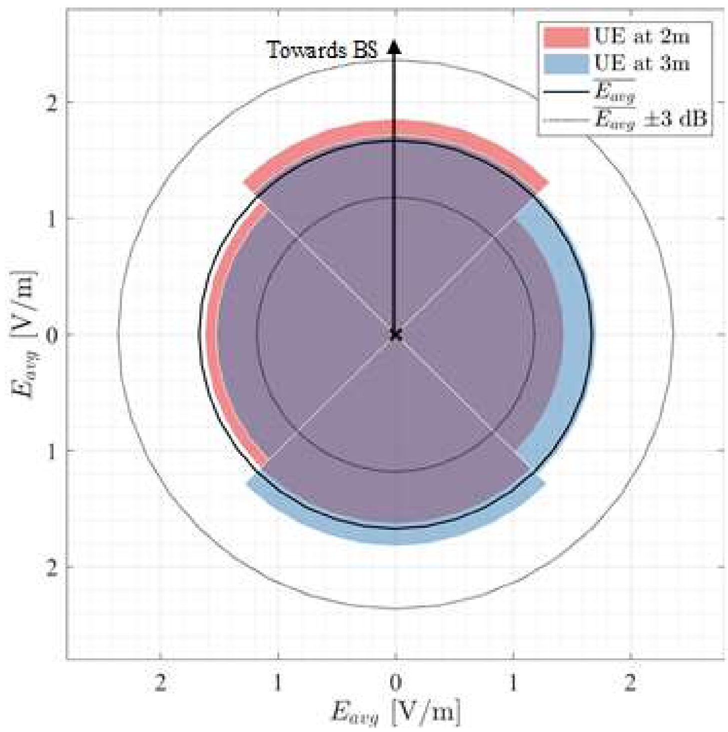

Figure 4: Average electric-field strength E_{avg} (V/m) at a fixed location (x) when the UE was positioned at either 2 m (red) or 3 m (blue) from the measurement probe (at x) in four directions: in front of (i.e., towards the BS), left of, right of, or behind the measurement probe. The purple area (i.e., the overlap) indicates the smaller of the two values. The average of the eight measurements is indicated with a black line, and the ±3 dB deviations (i.e., the measurement uncertainty) from this average with dotted lines.

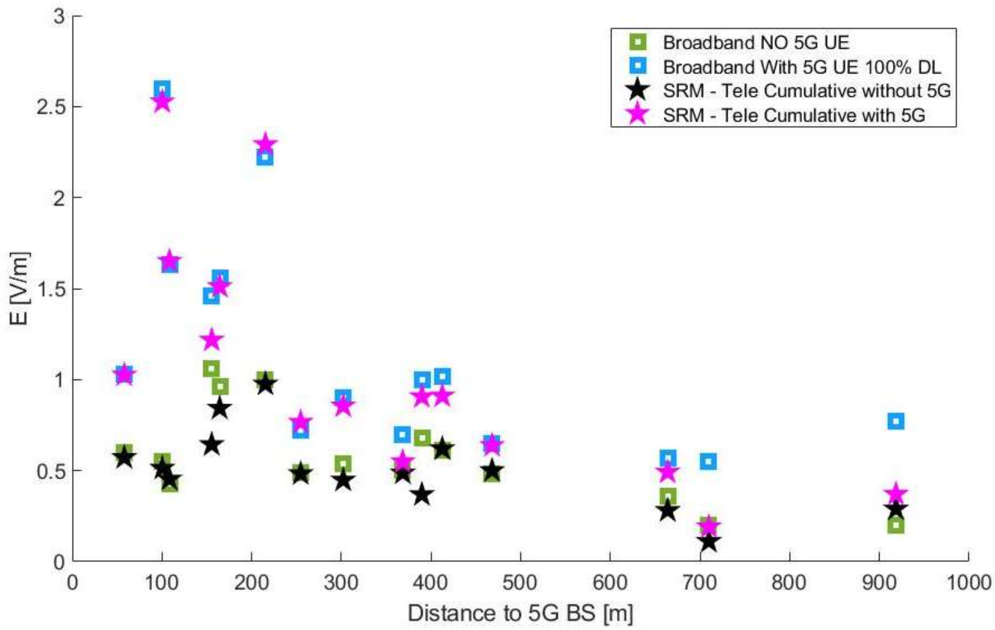

Figure 5: Measurement results with broadband and narrowband measurement system, organized by distance to the 5G base station. No differentiation is made between LOS or NLOS.

Table 1: Overview of 5G NR measurement sites.

Country	**Measurement site**	**CF [GHz]**	**5G BW [MHz]**	**$P_{out,BS}$ [W]**	**Height of BS* [m]**
Belgium	B1	3.78	40	20	29.4
	B2	3.65	100	100	28.5
The Netherlands	N1	3.68	40	6.4	21.5
	N2	3.75	100	160	43
Germany	G1	3.50	40	NA	12
Switzerland	S1	3.65	100	8.1	32.8

*Above floor level

Table 2: *Measurement data of electric-field values measured with different measurement equipment around 5G NR BS in Belgium, The Netherlands, Germany and Switzerland.*

Site	**Distance to BS [m]**	**1 active UE 100% DL**			**No active UE**	
		E_{max} [V/m]	**E_{avg} [V/m]**	**$E_{avg,SRM}$ [V/m]**	**E_{avg} [V/m]**	**$E_{avg,SRM}$ [V/m]**
B1	213	2.1$^{(1)}$	1.9$^{(1)}$	2.1	n.m.	n.m.
B2	300	1.6$^{(1)}$	1.9$^{(1)}$	1.8	n.m.	0.18
N1	127	1.0	0.9	0.8	n.m.	n.m.
N2	209	3.3	3.0	2.7	n.m.	n.m.
G1	62	4.7$^{(1)}$ / 4.2$^{(3)}$	4.9	n.m.	n.m.	n.m.
S1	166	0.6$^{(1)}$	0.5$^{(1)}$	0.4	0.05$^{(1)}$	0.18

n.m.: not measured, $^{(1)}$: with FSV, $^{(2)}$: with RTSA, $^{(3)}$: with R&S TSME scanner with Romes demodulation software

Table 3: Spectrum analyzer settings for sub-6GHz 5G NR signals

	Equipment	mode	CF	Span [MHz]	Additional remarks	Measurement time [min]
E_{avg}	SA[b]	frequency	CF of 5G NR channel	≥ BW of 5G-NR channel	Recommended settings can be found in [5]	6 / 30[d]
	Narda SRM	frequency	CF of 5G NR channel	≥ BW of 5G-NR channel	Not all settings are tunable (i.e., SWT) - select RBW so that the measurement time per sample is bigger or equal to the SS burst period	
	Tektronix RTSA (RSA306B)	IQ-sampling	CF of 5G NR channel	≥ BW of 5G-NR channel[c]	Emax and Eavg can be measured simultaneously	
E_{max} [a]	SA	zero-span	SS_{REF}	0	Recommended settings can be found in (7)	
	Narda SRM	scope	SS_{REF}	0	RBW = 1 MHz and time resolution = symboltime	[e]
	Tektronix RTSA (RSA306B)	IQ-sampling	CF of 5G NR channel	≥ BW of 5G-NR channel[c]		
	R&S TSME scanner with Romes demodulation software	Integrated automatic channel detection in predefined frequency range				

[a] based on SSB measurements
[b] SA with spectrogram mode, see [5] for detailed settings
[c] maximum acquisition BW is 40 MHz for the Tektronix RSA306B
[d] according to the averaging time recommended by the guidelines, but the actual measurement time can be shorter if the signal is deemed stable [12],[14]
[e] per axis otherwise the SWT is too long (i.e., >120 msec for tri-axial mode)