



Project: **SEAWave**

**Standard measurement methods to assess  
MaMIMO base stations exposures**

Work Package: WP3

Deliverable: D3.2

Deliverable No.: D10

## Abstract

Deliverable D3.2 presents the measurement procedures for the validation of the realistic simulations. The proposed procedures adhere to the IEC 62232:2022 [13], which outlines methodologies for assessing radiofrequency field exposure of wireless communication base stations among others. The deliverable first details the equipment and experimental settings, followed by a description of the environment and the rationale for evaluation point selection. Subsequently, it outlines the measurement types and procedures, describes the data collection and pre/post-processing methodologies, and finally presents the results accompanied by a comprehensive technical analysis. We observed Peak-to-Average Ratios for 5G-NR in the range of 2 to 3 dB for FTP-DL measurements, extrapolation factors ( $F_B$ ,  $F_G$ ,  $F_{PR}$ ) for SSS based exposure assessment ranged from 17.6 to 22.3 dB, and the proposed ray-tracing based methodology using real Equivalent Isotropically Radiated Power (EIRP) data showed exposure levels within a margin smaller than 4 dB compared with measurements. The numerical methodology provides valuable insights into the spatial distribution of exposure under real-world conditions, it can identify potential hotspots for detailed on-site measurements and can provide guidance for the operators or responsible authorities.

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## 1 Introduction

Work Package 3 (WP3) of the Scientific-Based Exposure and Risk Assessment of Radiofrequency and mm-Wave Systems from children to elderly (5G and Beyond) (SEAWave) project focuses on exposure monitoring from 5G New Radio (5G-NR) Massive MIMO base station antennas (BSAs). These advanced antennas utilize technologies such as beamforming and dynamic power management, which significantly affect the spatial and temporal characteristics of electromagnetic exposure [1], [2].

This study concentrates on the FR1 frequency band at 3.5 GHz, where empirical measurements were feasible. In contrast, for the FR2 band, only modelling was possible due to the limited availability of stand-alone FR2 sites and restricted access, which impeded validation efforts. Additionally, there is ongoing uncertainty regarding the widespread deployment of FR2 across Europe. FR2 (mmWave) signals are characterized by limited propagation range and poor penetration, necessitating dense network deployment and the integration of complementary technologies such as beamforming, smart repeaters, and reconfigurable intelligent surfaces (RIS) to mitigate these limitations [3]. These enhancements, while improving coverage and performance, may also increase the risk of creating localized exposure hotspots.

Some of the typical methods used for the assessment of MaMIMO BSAs include but are not limited to, In-situ (on-site) field measurements, System-level / ray-tracing simulations, Full-wave electromagnetic (EM) and hybrid EM tools, Statistical / stochastic modelling & Monte-Carlo, Phantom + dosimetry and chamber tests (OTA), and Channel sounding / protocol-aware captures. Direct in-situ measurements remain the primary method for assessing exposure in the vicinity of 5G NR Massive MIMO base stations. Calibrated broadband electric-field probes or spectrum analysers should be deployed at representative spatial points around the base station. Where possible, narrowband captures of 5G NR channels are recommended to separate contributions from control and traffic signals. Measurements must be time-averaged in accordance with regulatory guidelines, while short-term peaks may be recorded to quantify dynamic beam behaviour. This approach provides empirical data that serve both for compliance evaluation and validation of numerical models. [4][5][6] Deterministic ray-tracing simulations provide a system-level characterization of electromagnetic field distributions in realistic propagation environments (e.g., urban macro, suburban, or indoor). Building and terrain geometry, material parameters, and antenna array characteristics are included to reconstruct multipath propagation and beam dynamics. The outputs typically include spatial maps of power density and electric field levels. When combined with traffic models, raytracing enables time-averaged exposure estimations over large areas that are impractical to measure comprehensively. [7] Full-wave solvers, such as Finite-Difference Time-Domain (FDTD) or Method

of Moments (MoM), are used when detailed near-field effects or human exposure interactions must be studied. These methods allow the calculation of local specific absorption rate (SAR) distributions in anatomical phantoms, or the evaluation of mutual coupling between antenna elements in a dense array. While computationally intensive, full-wave modelling provides the highest fidelity and is essential when exposure occurs within the reactive or radiating near-field of the base station antenna. [8] Because Massive MIMO base stations employ dynamic, user-dependent beamforming, exposure cannot be fully characterized by static or worst-case assumptions. Monte Carlo and stochastic geometry methods allow the simulation of multiple user locations, traffic loads, and beam schedules to derive statistical distributions of exposure levels. This results in metrics such as the realistic maximum, median, or 95th percentile of power density over time. Such probabilistic modelling captures the inherent variability of exposure and avoids overestimation that arises from continuous full-power assumptions. [9] Tissue-equivalent phantoms and over-the-air (OTA) chamber setups are employed to translate incident fields into biologically relevant exposure metrics, such as SAR. This approach is particularly relevant for evaluating occupational scenarios or bystander exposure near antennas. By reproducing controlled beam patterns from Massive MIMO arrays in anechoic or reverberation chambers, researchers can assess realistic body coupling effects under repeatable conditions. This methodology complements in-situ and simulation studies by providing experimental dosimetric data. [10] In addition to broadband field strength measurements, it is recommended to perform protocol-aware captures of the 5G NR signal. This can be achieved by recording control and traffic channels, as well as beamforming weights when such information is accessible.

To complement the experimental exposure assessment methodologies, Deliverable 3.1 of the SEAWave project investigated realistic simulation environments. These environments were designed to replicate representative deployment scenarios of 5G NR Massive MIMO base stations, thereby enabling controlled evaluation of exposure conditions experimentally. [12] (D3.1)

This deliverable presents the measurement procedures for the validation of the realistic simulations. The proposed procedures adhere to the IEC 62232:2022 [13], which outlines methodologies for assessing radiofrequency field exposure of wireless communication base stations among others. Additionally, other relevant references such as [14] and [15] are incorporated to enhance the accuracy and effectiveness of the measurements. This report is structured to first detail the equipment and experimental settings, followed by a description of the environment and the rationale for evaluation point selection. Subsequently, it outlines the measurement types and procedures, describes the data collection and pre/post-processing methodologies, and finally presents the results accompanied by a comprehensive technical analysis.

## 2 Methodology

In this section the measurement methodologies are outlined and categorized into three primary types: overview, file transfer protocol – downlink (FTP-DL), and SSS measurements, hereafter referred to as Types 1, 2, and 3, respectively. For all measurement types, it is recommended that the technician maintains a minimum distance of two meters from the probe, preferably positioning themselves behind or to the sides of the probe. [14]

### 2.1 Measurements

#### 2.1.1 Equipment

As detailed in Table 1, a spectrum analyzer (SA) is utilized with complementary components such as a triaxial antenna to measure the electromagnetic field strength at the designated evaluation point (EP). To minimize potential interference introduced by the measurement setup, it is recommended to mount the antenna and associated equipment on non-metallic tripods, preferably constructed from wood or plastic materials.

The recommended measurement configurations are outlined in Section 2.1.3. For FTP downlink (DL) measurements, a user terminal (UT) capable of sustaining a DL connection is required. Optionally, a smartphone integrated with a drive test tool (e.g., QualiPoc) may be employed to enhance data acquisition and logging capabilities. Accurate EP coordinate data is essential for post-processing and validation. Therefore, the inclusion of a GPS module is advised to ensure precise geolocation logging throughout the measurement campaign.

Table 1. List of equipment and examples for different measurement types.

| Device                | Example                              |
|-----------------------|--------------------------------------|
| Spectrum analyser     | NARDA SRM-3006 + RF cable 3602/02    |
| Triaxial probe        | Three-axis antenna (E-field) 3502/02 |
| User Terminal         | Phone equipped with QualiPoc         |
| Wooden/Plastic tripod | -                                    |

All measurement equipment is maintained in accordance with the annual calibration procedures specified and performed by the manufacturer. This ensures the accuracy and reliability of the recorded data.

To ensure measurement consistency and reliability, multiple repetitions are conducted at the same location, particularly for Overview and FTP downlink (DL) measurements. This repetition serves a dual purpose: it verifies the stability of the measurement setup and enables the analysis of temporal variations in electromagnetic field (EMF) exposure levels.

For SSS (Synchronization Signal Block) measurements, the repetition requirements are less stringent. Since broadcast beams are typically stable over time, a limited number of repetitions is sufficient to obtain representative data.

## 2.1.2 Test Environment & Setups

### 2.1.2.1 Measurement locations

Evaluation points are selected in accordance with the guidelines outlined in Annex A of [13], within evaluation regions III-I and III-M. These points are positioned in the far-field region of the base station and encompass areas characterized by either single reflectors (e.g., ground surfaces) or multiple reflectors (e.g., buildings and other urban structures).

### 2.1.2.2 Overview Setup

In this configuration, the probe is placed at an arbitrary distance from the base station antenna, without the presence of a controlled user terminal (UT) in the environment. It is important to note that other users may be active nearby, potentially influencing the measurement conditions. This setup closely aligns with the Case A measurements described in Section 6.3.4 of [13], with all relevant parameters matched.

From the overview measurements the 6-minute average rms e-field on the EP is recorded. This type of data provides insights into scenarios where an active UT is not in the vicinity of the probe. Such scenarios grasp the real-world noise and interference from the UTs in the vicinity of the EP. Additionally, the results of this type of measurement can provide information on the exposure of non-users.

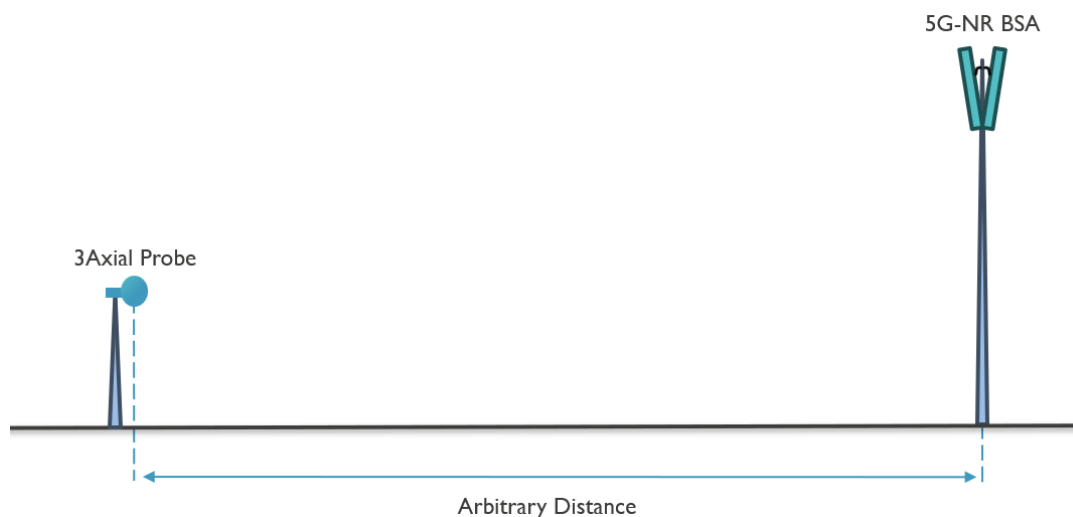


Figure 1. Setup of the overview measurement routine.

### 2.1.2.3 FTP-DL Setup

In this configuration, the user terminal (UT) is located at an arbitrary distance from the base station antenna (BSA), while the probe is positioned at a fixed distance of 2 meters from the UT along the direct line connecting the BSA and UT. This arrangement closely corresponds to the Case B measurements described in Section 6.3.5 of [13], aligning with most relevant aspects. The primary distinction lies in the explicitly defined minimum probe-to-UT distance of 2 meters, as specified in [14].

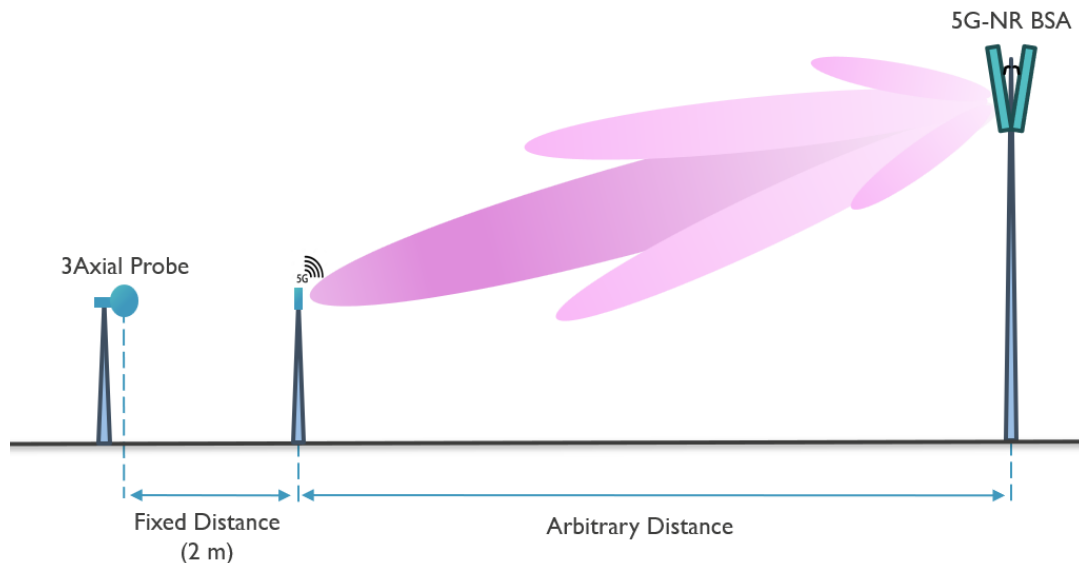


Figure 2. Setup of the FTP-DL measurement routine.

### 2.1.2.4 SSB Setup

This measurement was conducted using the same configuration as described in the Overview section, without introducing any additional components or making modifications to the setup.

## 2.1.3 Measurement procedure

### 2.1.3.1 Measurement flowchart

As illustrated in Fig. 3, the measurement process starts with site analysis to select a base station that provides 5G-NR coverage. The site analysis also considers the location of the evaluation points based on 2.1.2.1. Further relevant recommendations can be studied in Section 5.

The measurement methods should be selected based on the intended application, investigated metric, and available tools. After selecting the measurement method or a combination of them, if a dynamic environment or traffic is investigated, multiple repetitions of the measurements are performed for a statistical analysis between the routines.

After the measurements are performed according to 2.1.2, 2.1.3, and 2.1.4, the data of multiple sources or measurements can be aggregated in groups based on location and time. This provides the opportunity to compare the processed results based on those titles across measurement types. If multiple repetitions are necessary, the preferred process is to start with broadband

and/or FTP-DL measurements and finish with SSS measurements based on the conclusions in section 5.

The recorder data undergoes a structured preprocessing phase as outlined in Section 2.2.1. During this step, the raw data is standardized and formatted according to its original structure to ensure compatibility with subsequent processing stages.

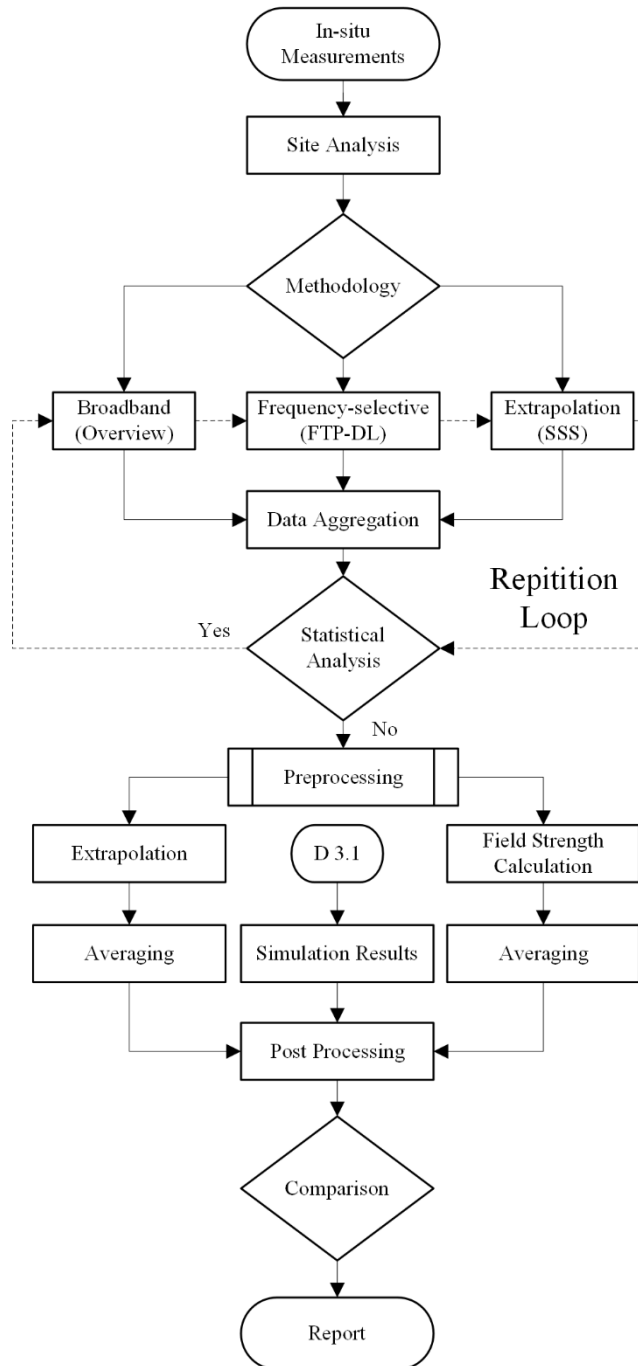


Figure 3. In-situ measurement flowchart for EMF exposure assessment.

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In the processing phase, the prepared input data is utilized based on its type. Specifically:

- For field strength assessment, the data is processed in accordance with Section 2.2.2.1.
- For extrapolation purposes, the procedures described in Section 2.2.2.2 are applied.

Following processing, the data enters the post-processing phase, where it is further refined for analysis. This includes averaging operations as specified in Section 2.2.2.3. The resulting data is then used for comparative analysis with measurement results, as detailed in Section 2.2.3.

#### *2.1.3.2 Overview measurements:*

This type of measurement enables in-situ assessment of ongoing electromagnetic field (EMF) activity and provides an initial evaluation of exposure levels in scenarios where the user terminal (UT) is not actively served near the evaluation point (EP). It inherently captures the influence of other active users and environmental interactions, offering a representative approximation of the prevailing exposure conditions in the area. The measurements are conducted in accordance with the configuration detailed in Section 2.1.2.2 and the operational settings specified in Section 2.1.4.

#### *2.1.3.3 FTP-DL measurements:*

This type of measurement is designed to evaluate electromagnetic field (EMF) exposure at and around an active user terminal (UT) that is requesting substantial resources from the base station antenna (BSA). These measurements are particularly useful for validating simulation outcomes. It should be noted that the accuracy of such simulations is contingent upon the capabilities and features supported by the selected software package. The measurements are performed in accordance with the setup described in Section 2.1.2.3 and the operational settings outlined in Section 2.1.4.

#### *2.1.3.4 SSB measurements:*

For measurements based on broadcast signals, any of the following signal blocks can be employed, PSS, SSS, and PBCH. The principle of this method is to measure the signal strength of a group of resource blocks and extrapolate it to consider different scenarios. The formulation is outlined in section 2.2.2.2.

### 2.1.4 Settings & Parameters

Table 2 outlines the measurement settings used across the study. Three distinct measurement routines are considered, each with a combination of common and routine-specific parameters. The primary differences between the routines include:

- Centre frequency or frequency band
- Type of recorded data
- Duration of the measurement routine
- Setup-dependent configurations

These variations are designed to accommodate the specific objectives and constraints of each measurement scenario.

Table 2. General parameters for measurement routines.

| Parameter                         | Overview     | FTP_DL        | SSB            |
|-----------------------------------|--------------|---------------|----------------|
| Frequency center or band          | 700-4000 MHz | FR 1          | F <sub>c</sub> |
| SCS                               | -            | -             | 30 KHZ         |
| Resolution bandwidth* (RBW) [MHz] | 1            | 1             | -              |
| Measurement Unit                  | V/m          | V/m           | V/m            |
| Data type                         | ACTUAL       | ACTUAL        | ACTUAL         |
| Sampling rate                     | MAX          | MAX           | -              |
| Routine Duration [min]            | 6            | 6             | 2              |
| Probe height [m]                  | 1.5          | 1.1, 1.5, 1.7 | 1.5            |
| Phone height [m]                  | -            | 1.5           | -              |
| Probe to phone distance [m]       | -            | 2             | -              |

\* This is the finest RBW possible selected with the SRM-3006.

The resolution bandwidth of the measuring equipment is kept consistent across all types of measurements. The frequency bandwidth or centre frequency depends on the channel under study, which is related to the available SIM card and service provider. The sensitivity is adjusted on site depending on the electric field level.

It is recommended that the reporting unit for all measurements use  $V/m$  to avoid additional steps to compare the output data. The sampling rate of measuring equipment is usually limited to the sweeping speed of the band of interest. As it is intended to investigate the highly dynamic behavior of the EMF exposure among other factors such as peak to average ratio, it is recommended to record the readings at maximum sampling rate in all scenarios. The measurement duration is preferred to be in line with the averaging of the counter data for validation if this data is available, otherwise 6 minutes is considered.

Probe height is based on the guidelines in IEC 62232, which specify the heights to be considered for spatial averaging.

Phone to probe distance is always maintained at 2 meters away to minimize picking up any UL influence on the probe. This has been mainly investigated for LOS measurements and further investigation is required for NLOS measurements. [4]

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## 2.2 Data processing

### 2.2.1 Pre-processing

#### 2.2.1.1 *Data Cleaning*

In this step corrupted or incomplete records (e.g., underutilized FTP-DL measurements, missing GPS coordinates, signal dropouts) are excluded from the data. Also, noise or irrelevant signals, especially if the measurement includes unintended sources can be filtered out.

#### 2.2.1.2 *Time Synchronization*

In this step data from measurements are aligned based on timestamps with between multiple data sources (e.g., measurement data, device logs, GPS logs, counter data).

#### 2.2.1.3 *Frequency Filtering*

In some measurement types a larger bandwidth might be measured. In this step relevant frequency bands (e.g., 5G NR FR1 or FR2) are selected from the data.

#### 2.2.1.4 *Spatial Filtering*

Based on the measurement location and available data logs, some EPs might experience an unstable connection to the BSA or the target technology generation. These EPs are filtered out after careful consideration of the data from different sources that can clarify whether the connection has been established with the BSA under study or not. (e.g. devices equipped with a drive test tools such as QualiPoc provide Cell ID information in their recordings.)

#### 2.2.1.5 *Calibration and Correction*

Depending on the reported data of the measuring equipment, an optional step is to consider a calibration or correction. (e.g., antenna gain, cable loss) In case of SRM-3006, this has been already considered in the reported data and only the uncertainty of the measurements should be considered in the reporting step. [5]

#### 2.2.1.6 *Unit Conversion*

Measurements are sometimes performed in different units or aggregated from different sources; In this case, the unit for the recorded data should be unified in unit for further processing.

#### 2.2.1.7 *Data Aggregation*

Depending on the type of study, measurements can be grouped by location, time, signal type, and measurement type.

#### 2.2.1.8 *Metadata Integration*

The recorded data from measurements can be merged with GPS data, environmental conditions, notes, or network configuration. In this step, measurements are tagged with an ID that can separate individual data groups based on the data aggregation step.

## 2.2.2 Processing

### 2.2.2.1 Field Strength Calculation

In case of a single-axis probe, a correction factor is required to scale the measurement data according to the manufacturer information. If such information is not available, additional steps are required to derive a case dependant correction factor.

In case of triaxial probes, the combination of the recorded data from each antenna axis should be considered. This is necessary since the electromagnetic fields can through their interactions, change the polarization of the propagated fields. (e.g. in case of devices like SRM-3006, which already considers the axial components and provides the processed recordings with an option to report them separately as well.)

If the recordings are in the form of raw measurements, they should be converted to RMS field strength for comparison and further processing according to equipment manufacturer guidelines.

### 2.2.2.2 SSS-Based Extrapolation

For broadcast-based measurements, the processing of recorded data depends on the specific broadcast signal being measured. The average power of the resource elements is influenced by the number of utilized resource blocks within the signal. As shown in Fig. 5, the PSS, SSS, and PBCH signals occupy one symbol in time and 127, 127, and 240 subcarriers in the frequency domain, respectively. Based on this information, the measured electric field strength corresponding to a single resource block can be calculated by normalizing the total measured field strength to the number of subcarriers associated with the signal. This normalization enables a consistent comparison across different broadcast signals and facilitates accurate estimation of exposure levels per resource block.

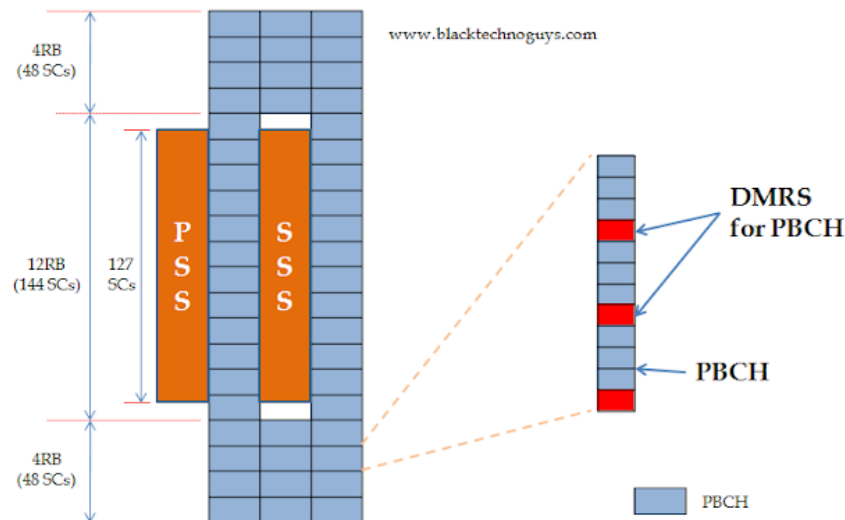


Figure 4. Resource allocation for SSB signals.

$$\bar{E}_{rms,RE} = \frac{\bar{E}_{rms,meas}}{\sqrt{N_{subcarrier}}} \quad (1)$$

Since the electric field strength of each resource element has been extracted based on Equation (1), the methodology outlined in Equation E.16 of [13] can be applied to estimate the maximum extrapolated exposure. Under full bandwidth utilization, the channel provides 273 subcarriers per symbol, with a subcarrier spacing (SCS) of 30 kHz and a total bandwidth of 100MHz. Accordingly, the time-domain duty cycle ( $F_{TDC}$ ) and power ratio ( $F_{PR}$ ) are both equal to 1, and the bandwidth ( $F_{BW}$ ) is calculated as  $F_{BW} = 12 \times 273 = 3276$ . It is important to note that the radiation pattern of broadcast signals differs from that of traffic signals. Therefore, a gain correction factor ( $F_{extBeam}$ ) is considered, as referenced in [17]. Similarly, a power correction factor ( $F_P$ ) may also be applicable, given that hardware-based beamforming can extend the coverage range. However, due to the proprietary nature of such implementation details, this information is not publicly accessible, making it challenging to accurately incorporate these correction factors.

### 2.2.2.3 Spatial and Temporal Averaging

The data can be aggregated based on location and time for performing spatial or temporal averaging. This step provides additional insights for both individual and cross-study comparison.

## 2.2.3 Post-processing

### 2.2.3.1 Exposure Assessment

This step is for comparing the processed data against the relevant regulatory limits and providing a percentage representation. (e.g., ICNIRP, FCC)

### 2.2.3.2 Statistical Study

Extraction of the statistical metrics such as mean, peak, standard deviation, percentiles from different aggregations can provide insights into the exposure variations and levels. Also, these statistical metrics can be used to validated and compare different methodologies.

### 2.2.3.3 Visualization and Mapping

Multiple types of graphical representations can be introduced in this step. 2D plot that present the power distribution over the field of view of the antenna, statistical plots, line plot for trends. (e.g. generating heatmaps or contour plots of field strength across geographic areas or Plot time series of exposure levels or frequency spectra.)

### 2.2.3.4 Simulation Validation

Compare measured values with simulated EMF distributions and quantify deviations and validate model assumptions.

### 2.2.3.5 Reporting and Documentation

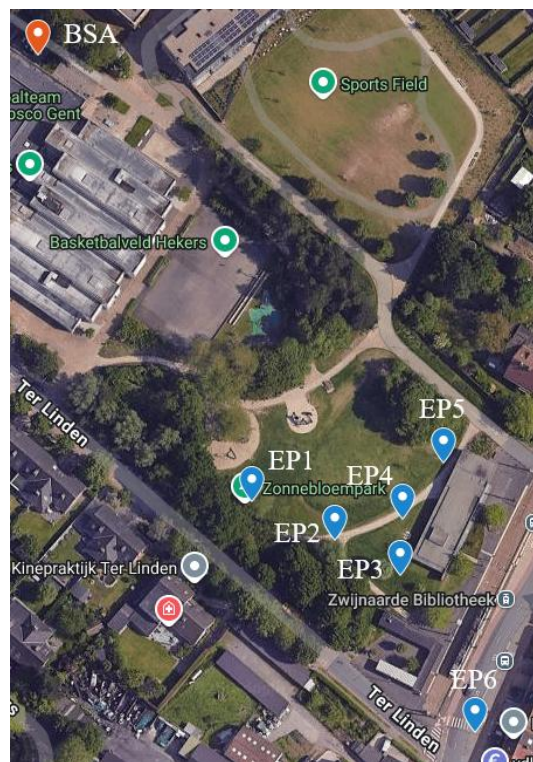
Format results for inclusion in technical reports or compliance documentation and include metadata (e.g., GPS coordinates, measurement conditions, equipment settings).

### 3 Case Study

#### 3.1.1 FTP-DL Measurements

As shown in Fig. 6, the area selected for the investigation of this report is a publicly accessible park in a suburban area of Gent in Belgium. The number of buildings is limited and, in most cases, only one or two buildings are in the 5 m vicinity of the probe. This area is dominantly covered by a sectoral antenna of a 5G-NR BS employing MaMIMO and reciprocity-based beamforming. All EPs are in the LOS and the 120° horizontal field of view of the sectoral antenna.

The other signals over the active spectrum in the area of interest (AoI) are ignored as the study focuses on FR1 (3.5 GHz), and we are interested in the operational spectrum over 3700 to 3800 MHz.



**Figure 5.** Selected site and evaluation points in the coverage area of a 5G-NR MaMIMO BSA. Red marker on the top left corner indicates the location of the BSA and the blue markers indicate the numbered EPs.

The selected exposure metric is the time-averaged electric field strength in V/m or dB $\mu$ V/m. The unit and sensitivity level is selected according to the ambient sources and such that the measuring device is not overdriven.

Since the 5G NR BSA is utilizing beamforming, to attract a traffic beam, a UT equipped with QualiPoc was employed according to the measurement type 2.

### 3.1.2 SSS Measurements

For SSB-based measurements, the 5G-NR mode of the Narda SRM-3006 is utilized. This mode performs code-selective power level measurements, specifically targeting the Secondary Synchronization Signal (SSS) of 5G cells. To ensure accurate configuration, the Subcarrier Spacing (SCS) and the centre frequency of the PBCH block must be known beforehand. This measurement method is compatible with both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) modes. [15]

To confirm the correct base station antenna (BSA), drive test tools (e.g. QualiPoc) are used to extract the cell-ID, which is then matched during SSS-specific measurements. The 2-minute average electric field strength in mV/m is recorded across all broadcast beams, including those from adjacent subsectors. These measurements help distinguish between static broadcast beam exposure and dynamic traffic beam behaviour, which cannot be captured without full BSA control.

For this case, the same EPs as Case Study A have been considered

### 3.1.3 Overview measurements

Overview measurements were performed on the same EPs as the Single UT campaign following the procedure in 2.1.3.2 and the settings in 2.1.4.

## 4 Results & Observations

### 4.1 Overview measurements

Figure 8 presents the 6-minute time-averaged electric field (E-field) strength recorded at multiple evaluation points (EPs) covering only the monitored 5G-NR frequency band from 3700 to 3800MHz. These measurements incorporate the expanded uncertainty associated with the measurement setup, as specified by the equipment manufacturer [18]. The uncertainty values are based on the specifications and configuration details outlined in Section 2.1.1, ensuring that the reported field strengths reflect both the measurement accuracy and the limitations of the instrumentation.

As illustrated in Fig. 8, the variation in recorded E-field strength between multiple measurements on each evaluation point is less than 1 dB. This minimal variation suggests that short-term fluctuations, occurring over intervals of 6 to 15 minutes, are generally negligible. Furthermore, the consistency in background noise and interference levels across these measurements indicates stable environmental conditions during the measurement period. This observation is consistent with the time intervals between successive measurements (6 to 15 minutes), reinforcing the reliability of the data collected within the specified temporal window.

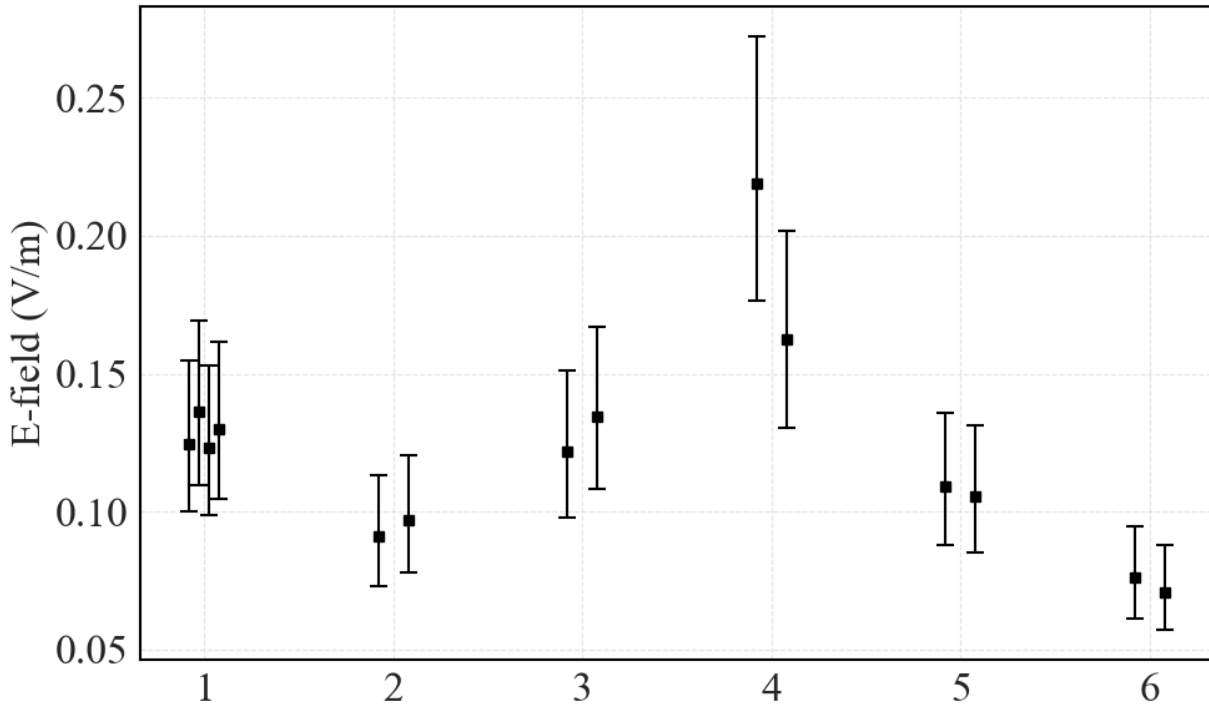


Figure 6. The 6-minute time-averaged electric field (E-field) strength at each evaluation point within the monitored frequency 5G-NR band from 3700 to 3800 MHz, including the setup expanded uncertainty of 1.89 dB.

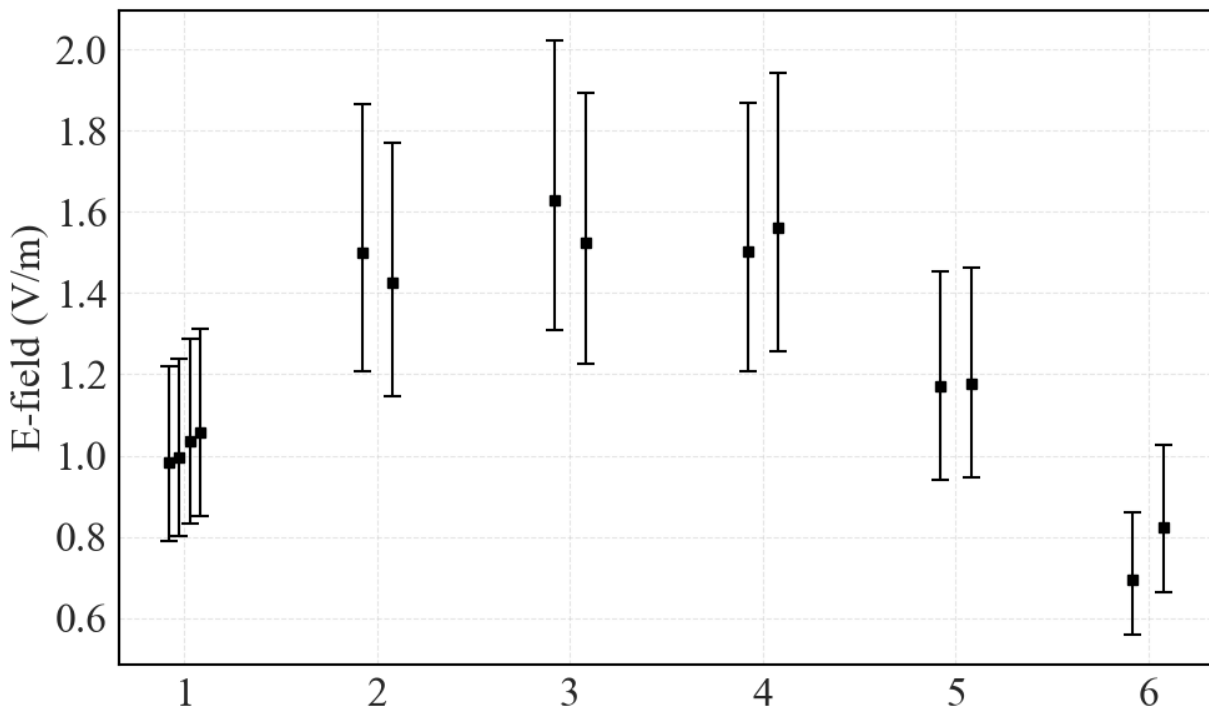


Figure 7. The 6-minute time-averaged electric field (E-field) strength at each evaluation point within the monitored frequency band from 700 to 4000 MHz, including the setup expanded uncertainty of 1.89 dB.

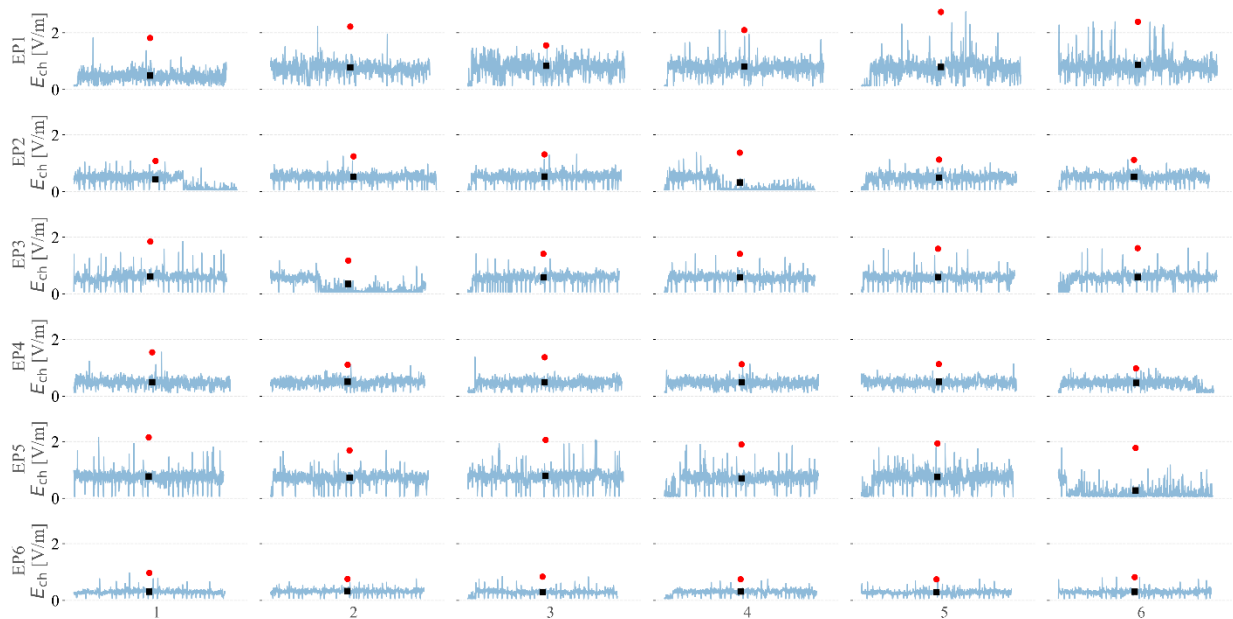
As shown in Figure 9, the results encompass the average E-field strength of the entire measured frequency band ranging from 700 MHz to 4000 MHz, including the monitored 5G-NR band previously presented in Figure 8. Even across this broader spectrum, the variation in E-field strength between consecutive measurements such as those conducted at EP1 which remains below 1 dB, indicating stable signal conditions over short time intervals.

However, at EP6, the deviation exceeds 1 dB, which may be attributed to specific channel activity or transient environmental changes occurring during the measurement period. This localized fluctuation highlights the importance of contextual factors in interpreting short-term EMF exposure variability. These factors can be noted during the measurements to provide more insights into the variations.

## 4.2 FTP-DL measurements

For the FTP downlink (FTP-DL) measurements, the maximum number of samples was recorded to enable a comprehensive and detailed analysis of the results. Figure 10 illustrates the channel-specific electric field (E-field) strength corresponding to each evaluation point (EP) and measurement identifier (ID) pair, denoted as (EP, ID).

In specific instances—namely (2,1), (2,4), (3,2), and (5,6)—a disruption in the user terminal (UT) connection was observed. This disruption resulted in a significant drop in the measured E-field strength, which in turn led to a lower average exposure for those cases. These anomalies highlight the importance of maintaining stable UT connectivity during measurement campaigns to ensure accurate exposure assessments.



**Figure 8.** Channel-specific electric field (E-field) strength recorded across multiple FTP-DL measurement identifiers (IDs) at various evaluation points (EPs), with overlaid indicators for average (black square) and maximum (red circle) E-field strength per (EP, ID) pair.

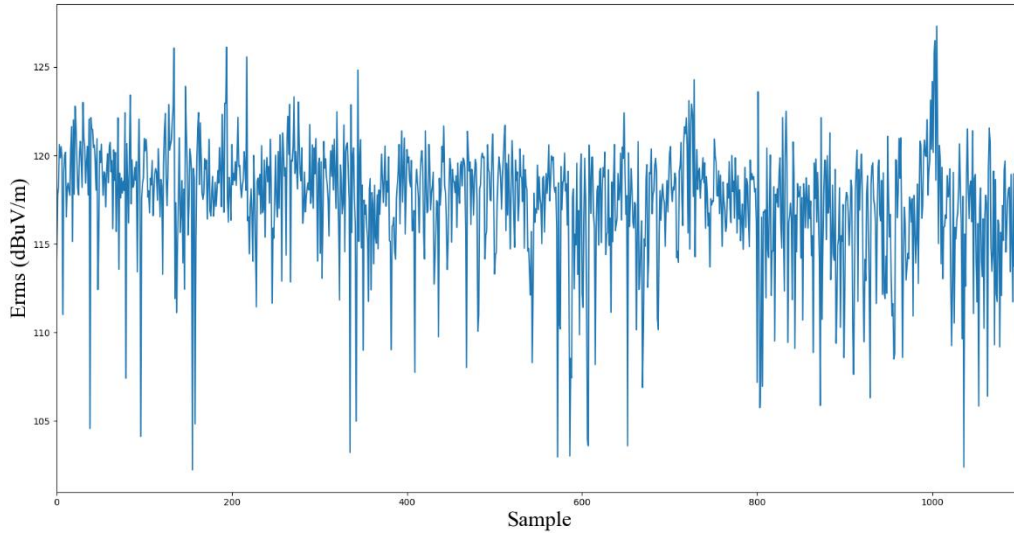


Figure 9. Detailed sample trace of an FTP-DL measurement showing channel-specific electric field (E-field) strength in dBµV/m over time.

Figure 11 shows a detailed example of the recorded E-field strength samples during an FTP-DL measurement. The channel-specific E-field strength exhibits significant fluctuations and does not appear to follow a consistent pattern. However, since exposure limits are defined based on time-averaged values, the raw data must be processed accordingly. Only the averaged E-field strength should be considered when comparing against the exposure limits specified in the relevant guidelines.

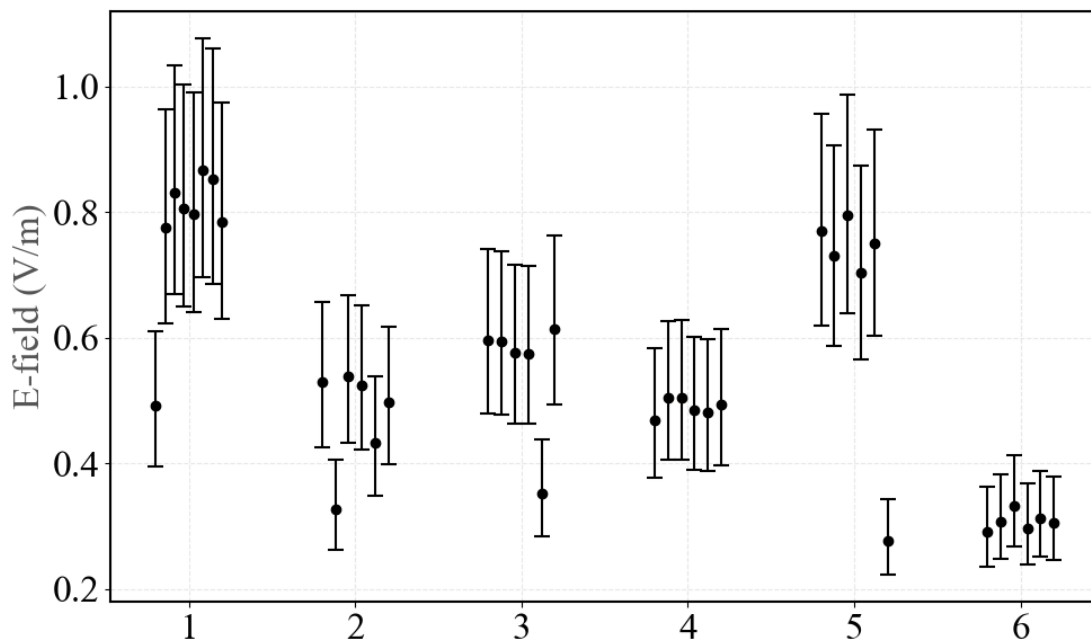


Figure 10. Averaged channel-specific E-field strength for multiple FTP-DL measurements on different EPs with whiskers for the expanded uncertainty of the setup equipment.

Figure 12 presents the average electric field (E-field) strength recorded for each FTP-DL measurement. An expanded uncertainty of 1.89 dB (coverage factor  $K = 2$ ), applicable to frequencies above 3 GHz, has been incorporated into the analysis in accordance with the specifications provided by the equipment manufacturer [18].

In addition to the previously identified (EP, MID) pairs with disrupted user terminal (UT) connections—specifically (2,1), (2,4), (3,4), and (5,6)—the pair (1,1) also exhibits lower-than-typical exposure levels. This deviation may be attributed to temporary connectivity issues or environmental factors affecting signal stability during the measurement period. However, the exact cause could not be conclusively isolated.

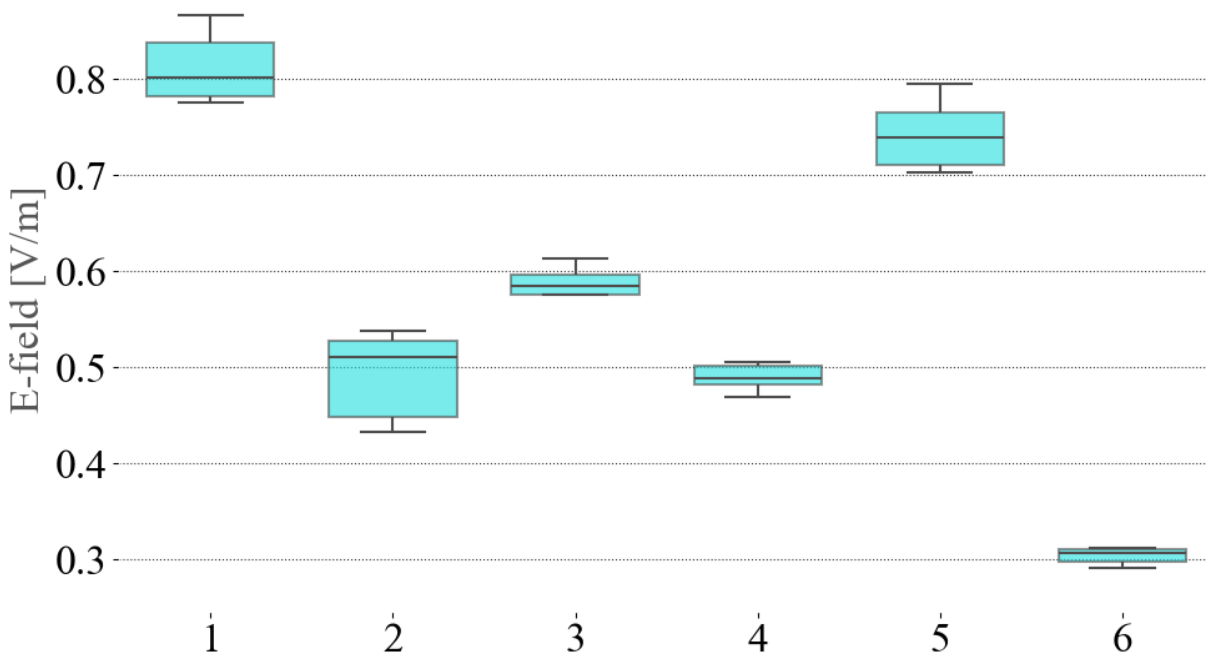


Figure 11. Boxplot of the FTP-DL measurement results on different EPs.

Figure 13 presents a boxplot illustrating the statistical distribution of E-field exposure levels across multiple FTP-DL measurements performed at each evaluation point (EP). The interquartile range (IQR) for all EPs remains below 2 dB, indicating minimal variability in the recorded values. This consistency demonstrates that the measurement process is highly reproducible within the typical one-hour timeframe required to complete a set of six measurements at each EP.

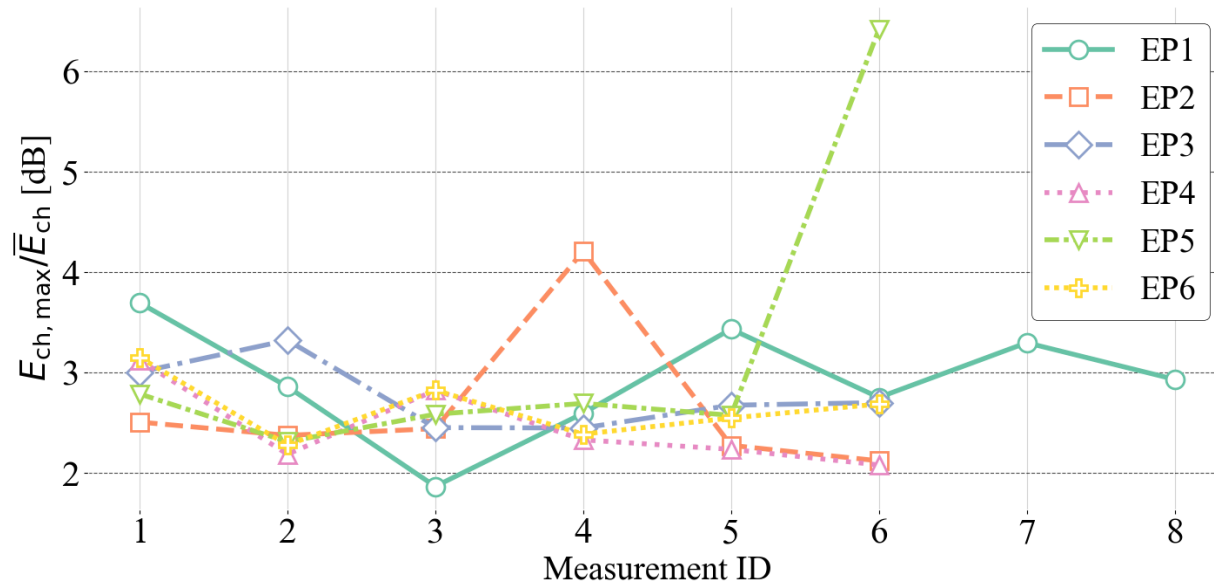


Figure 12. Power-to-Average comparison of multiple FTP-DL measurements on different EPs.

Figure 14 illustrates the Peak-to-Average Ratio (PAR) of the FTP-DL measurements. Different mobile network generations exhibit characteristic PAR values due to their underlying modulation schemes—for example, approximately 2 for a sinusoidal signal, 8.7 for GSM, 3.1–3.3 for UMTS-FDD, and 10–20 for WLAN [19]. In the current measurement campaign, where the user terminal (UT) maintained a stable connection with the base station antenna (BSA), the observed PAR values consistently ranged between 2 and 3 dB. This indicates a relatively uniform signal envelope, consistent with the expected behaviour for the tested configuration. Higher PAR values can be attributed to the low average or high peaks while considering the disruptions.

### 4.3 SSS measurements

In Figure 15, the results of multiple 2-minute measurements performed on the SSS signal are shown. They show a typical fluctuation, lower than 1 dB and only in one of the measurements (EP3) the fluctuations are more profound, yet do not exceed 2 dB. These results help with extracting the difference between the broadcast and the traffic signals on a real-world network. Their differences can be used to determine an extrapolation factor to consider the worst-case scenarios across EPs.

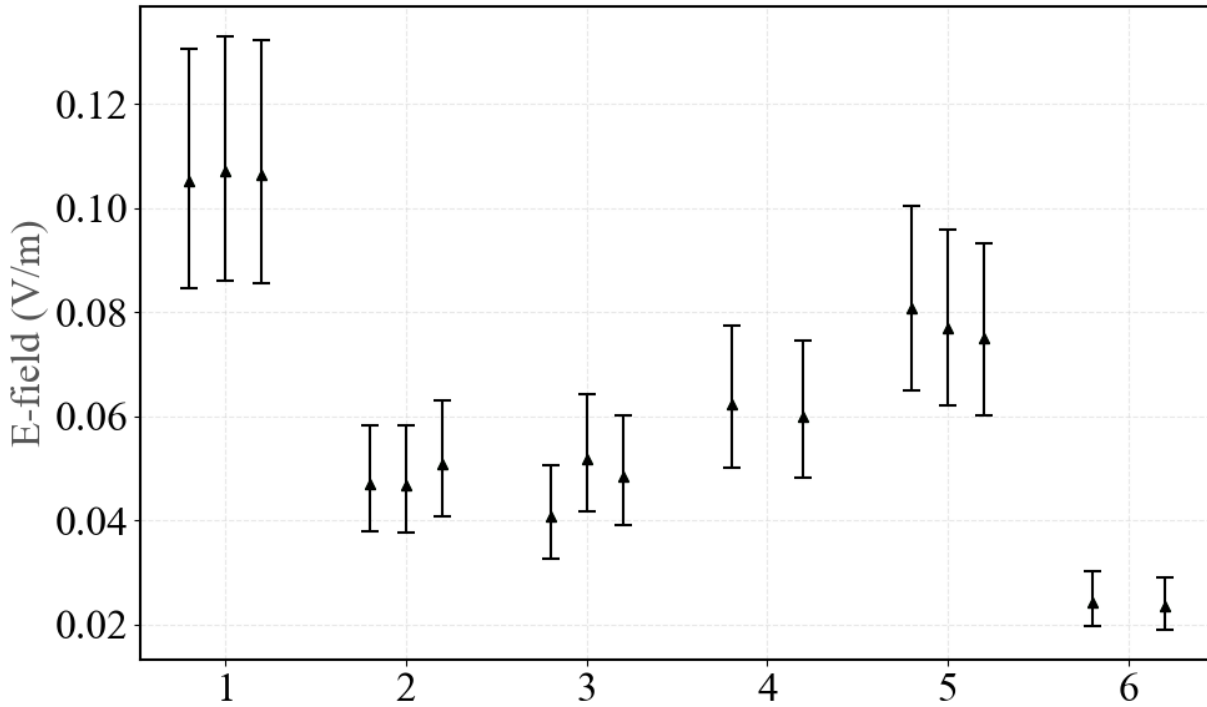


Figure 13. Extrapolated exposure based on SSS measurements without the effect of  $F_{extBeam}$  and considering the expanded uncertainty of the equipment setup.

#### 4.4 Comparative Results

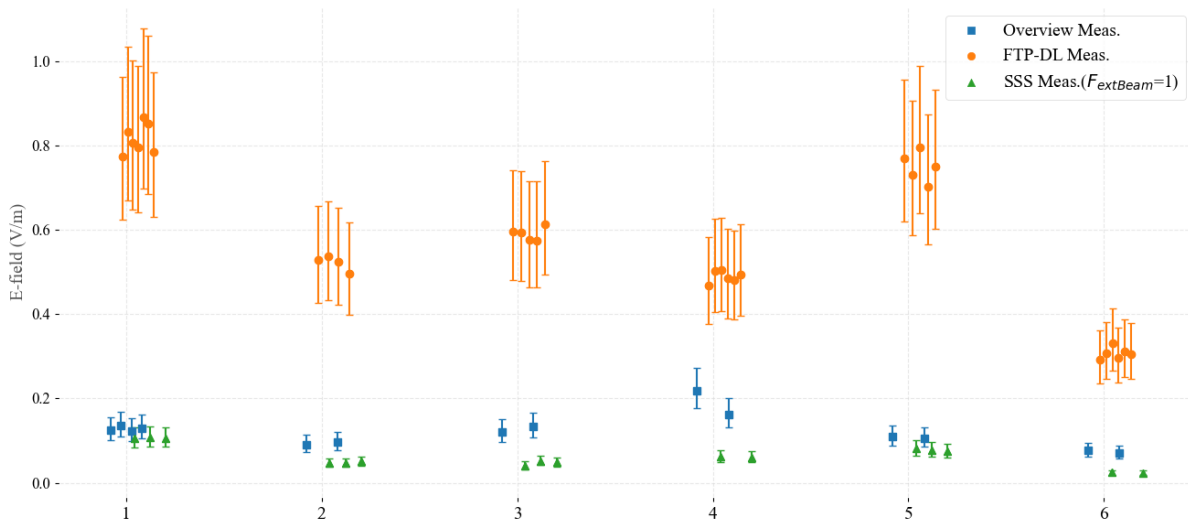
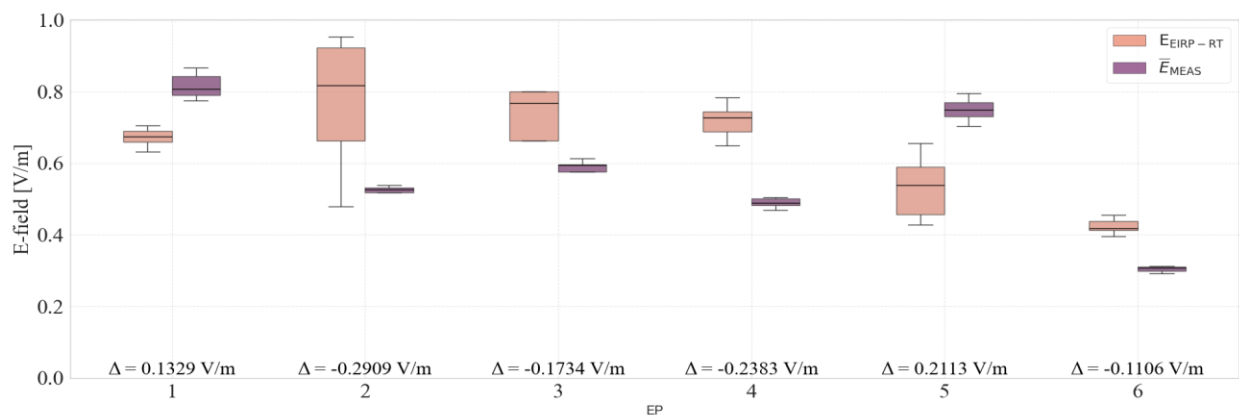


Figure 14. Comparison of the E-fields from Overview, FTP-DL, and SSS measurements extrapolated for maximum exposure without the effect of  $F_{extBeam}$  and considering the expanded uncertainty from the measurement equipment.

Figure 16 compares the electric field (E-field) strength obtained from different measurement approaches. The blue squares represent the overview measurement data, the orange circles

correspond to FTP-DL measurements, and the green triangles indicate values extrapolated from Synchronization Signal (SSS)-based measurements. The extrapolation assumes an  $F_{DC}$  of 75% and excludes the contribution of the  $F_{\text{extBeam}}$  (difference between traffic and broadcast gain),  $F_B$  and  $F_{PR}$ , since no information is available on these factors ( $F_B = F_{PR} = 1$ ). The observed difference between FTP-DL and SSS-based results provides an estimate for the extrapolation factor, effectively accounting for the combined influence of the missing parameters. In this case, a difference of 17.6 to 22.2 dB was observed between the median of the FTP-DL measurements and the SSS-based extrapolations for maximum exposure assessment without the effect of  $F_{\text{extBeam}}$ . This shows that a combined effect of different extrapolation factors ( $F_{PR}$ ,  $F_B$ ,  $F_{DC}$ ,  $F_{\text{extBeam}}$ ) for beamforming antennas in a real-world scenario can be comparable to the array gain (24.9 dB), which is much larger than 6 dB [17].



**Figure 15.** Comparison of the channel-specific E-field strength for EIRP-based ray tracing against FTP-DL in-situ measurements. The difference between the medians of the EIRP-based RT and 6-minute averaged FTP-DL measurements are shown above the horizontal axis.

Figure 17 shows the comparison of the simulated E-field strength of the EIRP-based ray tracing and the in-situ measurements overlaid with the uncertainty bar of the measurements for a confidence interval of 95%. The results show an approximation of the medians with a difference in the range of 1.56 to 3.76 dB. Although these fall outside of the uncertainty range of the measurements, the approximations are improved compared to the maximum extrapolation which is over exaggerating the exposure levels. The simulations overestimate the exposure except from EP1 and EP5 where exposure levels are underestimated. On EP1, the results stem from the destructive interference of the LOS and ground reflection rays as they have a phase difference of 217 degrees while contributing to 99.99% of the result and assigned the same EIRP value. On EP5, the EIRP data shows that during the measurements the BSA has been focused on a different direction than the one of the controlled-UT, resulting in a lower exposure estimation based on EIRP input data.

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## 5 Conclusions & Recommendations

### 5.1 Site Analysis

In configurations where 5G is deployed in a non-standalone (NSA) mode, relying on LTE as the anchor, it is essential to continuously monitor the connectivity status of User Terminals (UTs). This ensures that the UT remains connected to the 5G New Radio (NR) network and does not unintentionally revert to legacy communication technologies (e.g., LTE or 3G).

### 5.2 Overview Measurements

These measurements include the exposure from the uncontrolled active users in the area and the broadcast beams of the 5G-NR BSA during the measurement period. If the specific spectrum from 3700 to 3800 MHz is investigated, the E-field levels are much lower than the FTP-DL measurements. Yet, if the extended range covering the other bands is studied, the E-field levels are comparable to FTP-DL recorded levels.

### 5.3 FTP-DL Measurements

The results of FTP-DL measurements show that even in this case there are a lot of variations in channel-specific E-field levels over short time periods, and the behavior is unpredictable. Although averaging over specific time durations (6-min in this case) can produce stable and comparable results for exposure studies unless disruptions occur in the established link.

In addition, we determined the Peak-to-Average Ratio. The observed PAR values for 5G-NR in this study were generally in the range of 2 to 3 dB for FTP-DL measurements.

### 5.4 SSS Measurements

The results show minimal variation over time for the broadcast beam exposure suggesting a stable environment in terms of moving scatters. The extrapolation to a realistic maximum exposure that considers all the extrapolation factors such as  $F_B$ ,  $F_G$ ,  $F_{PR}$  is approximately in the range of 17.6 to 22.2 dB.

### 5.5 Simulation vs Measurements

The simulation tool evaluated in this study, based on Equivalent Isotropically Radiated Power (EIRP) data, was able to estimate exposure levels within a margin smaller than 4 dB. This tool can provide valuable insights into the spatial distribution of exposure under real-world conditions. Furthermore, it can help identify potential hotspots that warrant detailed on-site measurements and provide insights for the operators or responsible authorities.

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