Project: **SEAWave**

In situ validation of exposure assessment methodologies in FR1 and FR2

Work Package:	WP3
Deliverable:	D3.3
Deliverable No.:	D11

Abstract

Deliverable D3.3 presents the measurement results for the intercountry study of the measurement protocol discussed in Deliverable 3.2 [3]. The proposed procedures in D3.2 adhered to the IEC 62232:2022 [4] and IEC 62232:2025 [5], which outlines methodologies for assessing radiofrequency field exposure of wireless communication base stations among others. The deliverable first details the equipment and experimental settings following the protocols described in D3.2 [3] for each of the participating countries. Subsequently, it outlines the measurement types and environments considered in each country, and finally presents the results accompanied by a comprehensive technical analysis. The results of investigation on averaging duration indicate the possibility of reducing the measuring duration depending on the initial in-situ results for maximum realistic exposure assessment. We observed higher exposure levels in France and Slovenia in the range of 4 to 9 V/m with the lowest levels in Greece and Belgium in the range from 0 to 2 V/m for FTP-Download measurement routine. The Peak-to-Average ratios for 5G-NR were conservatively in the range of 1 to 4 dB for FTP-DL measurements across the participating countries. Partial SSS-based maximum extrapolation showed a difference of 8.5 to 10.3 dB between the assumed extrapolation factors and the real-world maximum exposure. Spatial averaging results suggested that 3-point averaging generally provides an overestimation of the exposure compared to the central point measurements. Also, the 3-point spatial averaging provides an estimation with variance of less than 5% from central point measurements.

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Deliverable Details

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Contents

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 measurements were performed in Belgium, France, Greece, and Slovenia. 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 as mentioned in D3.2 [3].

This deliverable presents the measurement results for the intercountry measurements to assess exposure from 5G-NR MaMIMO base stations. The proposed procedures were communicated to the partners and followed for comparability as detailed in D3.2 [3]. This report is structured to first detail the equipment and experimental settings used in the measurements performed by the participating countries, followed by information on data collection and processing. Subsequently, it outlines the measurement types and procedures used in each participating country and finally presents the results accompanied by a comprehensive technical analysis.

2 Methodology

The measurement methodology aligned with the approach outlined in D3.2 [3] and was applied across all measurements conducted in the included countries.

2.1 Measurements

2.1.1 Equipment

2.1.1.1 Belgium

As mentioned in Deliverable 3.2 [3], in Table 2.1, 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 [9]) 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 2.1 List of equipment and examples for different measurement types.

Device	Example
Spectrum analyser	NARDA SRM-3006 [6][7] + RF cable 3602/02 [8]
Triaxial probe	Three-axis antenna (E-field) 3502/02 [8]
User Terminal	Phone equipped with QualiPoc [9]
Wooden/Plastic tripod	-

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 Synchronization Signal Block (SSS) 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.

2.1.1.2 France

The measurements are carried out by ISO 17025 accredited laboratory following the ANFR measurement protocol that is in line with international standard EN IEC 62232:2025 [5].

Measurements are performed using a spectrum analyser (Narda SRM 3006), a suitable tri-axis antenna probe (Narda 3502/01) and an RF cable (Narda 3602/02), following the guidance provided in IEC 62232:2025 [5].

A wooden tripod is used to hold the measurement equipment to minimally perturb the fields during measurements.

Measurements are taken at 3 heights (1.10 m, 1.50, and 1.70 m), averaged over 6 min (or a lower period if the level averaged during such a period remains stable) and the final result is the spatial average of the levels measured at the 3 heights.

In addition to the accredited measurement, measurements with typical base station load profile have been performed as explained in B.4.2.5.4 of EN IEC 62232:2025 [5]. A smartphone is placed so that the base station serving beam(s) are directed towards the evaluation point. A download of a 1 GB data file from a Google drive has been used as typical load profile.

2.1.1.3 Greece

The measurements in Greece were conducted by RCL-AUTH which is an ISO 17025 and IEC 62232:2022 [4] accredited laboratory. The measurement equipment used by AUTH included a Narda Selective Radiation Meter (SRM-3006) [6][7] operating in Safety Evaluation mode, using “Conditional Storing” for sampling, connected to a Narda three-axis E-field antenna (420 MHz–6 GHz) [8] via a Narda SRM RF cable (9 kHz–6 GHz) [8]. The antenna was mounted on a non-metallic tripod (Berlebach, Report 8023) and positioned at the evaluation points/heights.

A Xiaomi 12 Pro running the EchoOne [10] application by Enhancell was used to perform FTP downloads while being locked to the 3.6 GHz band. The smartphone was mounted on a non-metallic tripod and positioned between the 5G-NR base station and the SRM-3006. A second mobile phone in flight mode was used to time the measurement duration and to take photographs of the setup.

2.1.1.4 Slovenia

The measurements in Slovenia were conducted by an ISO 17025 and IEC 62232:2022 [4] accredited laboratory. The measurement equipment used in Slovenia included a Narda Selective Radiation Meter (SRM-3006) [6][7] connected directly to a Narda 3502/01 three-axis E-field antenna (420 MHz–6 GHz)[8]. The antenna was mounted on a non-metallic tripod and positioned at the evaluation points at 3 heights (1.10 m, 1.50 m, and 1.70 m). Measurement protocol followed the requirements of the document Measurement Procedure for 5G-NF Exposure Assessment from [3]. On each measurement location, 4 measurements were conducted, one overview measurement at 1.5 m and three measurements under FTP-DL at 1.1, 1.5 and 1.7 m. Measurements were conducted in the Safety Evaluation mode, covering the whole frequency band of the analyzed base station from 3420 to 3520 MHz for FTP-DL and 700 MHz to 4 GHz for overview measurements. For each measurement, results were stored for 6 minutes with the

"Time Controlled Storing" functionality of the SRM-3006, with the option "as often as possible", resulting in more than 850 stored values for FTP-DL setup and more than 370 for overview setup. For FTP-DL mode, a mobile phone was used to download large files from a dedicated server.

2.1.2 Test Environment & Setups

The selection of measurement locations was carried out in accordance with the guidelines specified in Deliverable 3.2 [3]. Furthermore, all measurement setups, configurations, and procedures were implemented following the recommendations outlined in the same deliverable.

2.2 Data processing

Data processing follows the instructions mentioned in D3.2 [3]. The primary variation in processed data across countries stems from differences in the data importing process, as all measurements adhered to the procedure specified in D3.2 [3].

The impact of measurement duration was assessed by comparing different sampling aggregation times within a single 6-minute measurement, excluding measurements of shorter than 2 minutes from this analysis. Investigation on Peak-to-Average ratio was performed where time-series data was available. Spatial averaging was examined when detailed information on specific measurement points was available.

3 Measurements

3.1 Belgium

3.1.1 FTP-DL Measurements

As shown in Figure 3.1, the sites selected in Belgium are the roadside of a busy boulevard, a park in the suburban area, and an urban street in the city of Ghent. The number of buildings is limited in the first two sites and, in most cases, only one or two buildings are in the 5 m vicinity of the probe. The area under investigation is dominantly covered by a sectoral antenna of a 5G-NR BS employing MaMIMO and reciprocity-based beamforming. Most EPs are in the LOS and the 120° horizontal field of view of the sectoral antennas and only in the 3rd site EP9 and EP10 are in NLOS of the BSA.

Any 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.

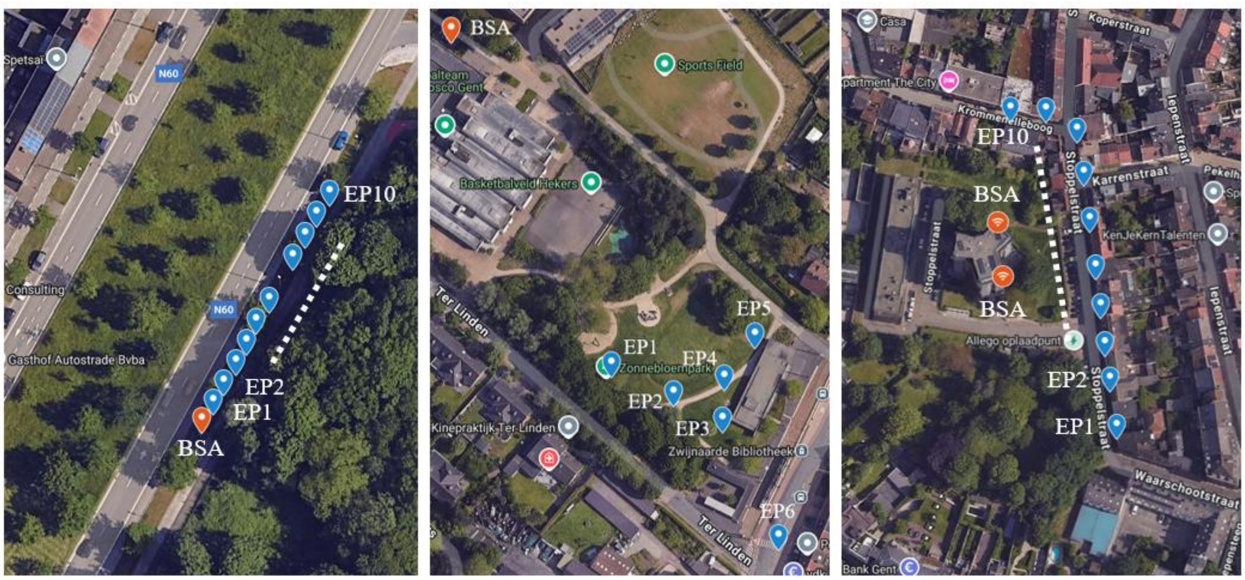

Figure 3.1. Selected sites and evaluation points in the coverage area of 5G-NR MaMIMO BSA. Red markers indicate the location of the BSA and the blue markers indicate the numbered evaluation points. EPs are 5 to 260 meters away from the base of the 5G-NR BSAs.

The selected exposure metric is the time-averaged electric field strength in V/m or dBµV/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 [9] was employed according to the measurement type 2, outlined in D3.2 [3].

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. [6]

To ensure that the correct base station antenna (BSA) is analysed, drive-test tools (e.g., QualiPoc) are used to extract the serving cell ID. This cell ID is then validated during SSS-specific measurements using the data reported by SRM.

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 FTP-DL measurements have been considered

3.1.3 Overview measurements

Overview measurements were performed on the same EPs as the FTP-DL measurements following the procedure in 2.1.3.2 [3] and the settings in 2.1.4 [3] on most EPs.

3.2 France

3.2.1 Configuration of measurements

All measurements were taken outdoors during the day, in direct view of the target site, in the street and at a distance of around 100 m (some examples are illustrated on Figure 3.2). The target sites have been chosen in Paris and are employing massive MIMO base stations for 5G NR 3.5 GHz band.

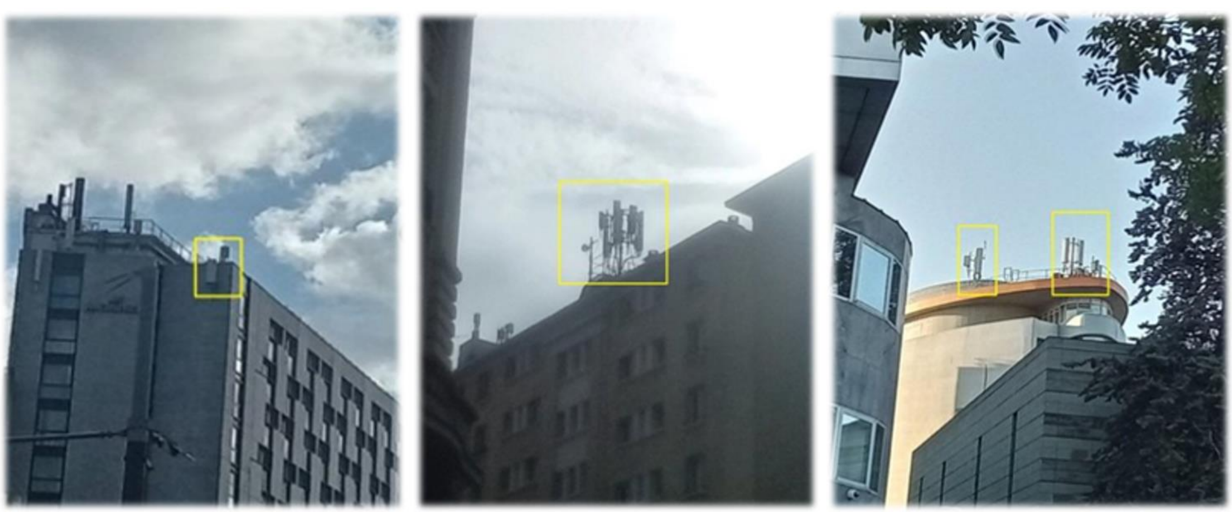

Figure 3.2. Three examples of measurement locations in line of sight of BS employing 5G in Paris, France.

3.2.2 DL measurements

The selected exposure metric is the time-averaged electric field strength in V/m. The DL measurements are performed at one height 1.5 m from the floor.

These downlink measurements give rise to:

- Measurement of the exposure level without downloading on the band of the operator installed in the 3.5 GHz site.
- Exposure averaged over the time taken to download a 1GB file on the operator's 3.5 GHz band.

3.3 Greece

As shown in Figure 3.3, measurements were performed on rooftop and in urban areas, on two sites in Thessaloniki, Greece. These measurements were performed for FTP-DL and Overview types and follow a similar setting based on [3]. Measurements performed on the rooftop include data from both providers A (3.6-3.7 GHz) and B (3.45-3.6 GHz) in Greece, although in the urban area only the exposure from provider A has been investigated. On all sites a 9-point spatial averaging measurement was performed totalling the number of measurements to 30 when including both types. The measurements were performed on a 9-point spatial grid following the standard guidelines of IEC 62232:2022 [4]. Overview measurements were performed at the central point of the FTP-DL measurements.

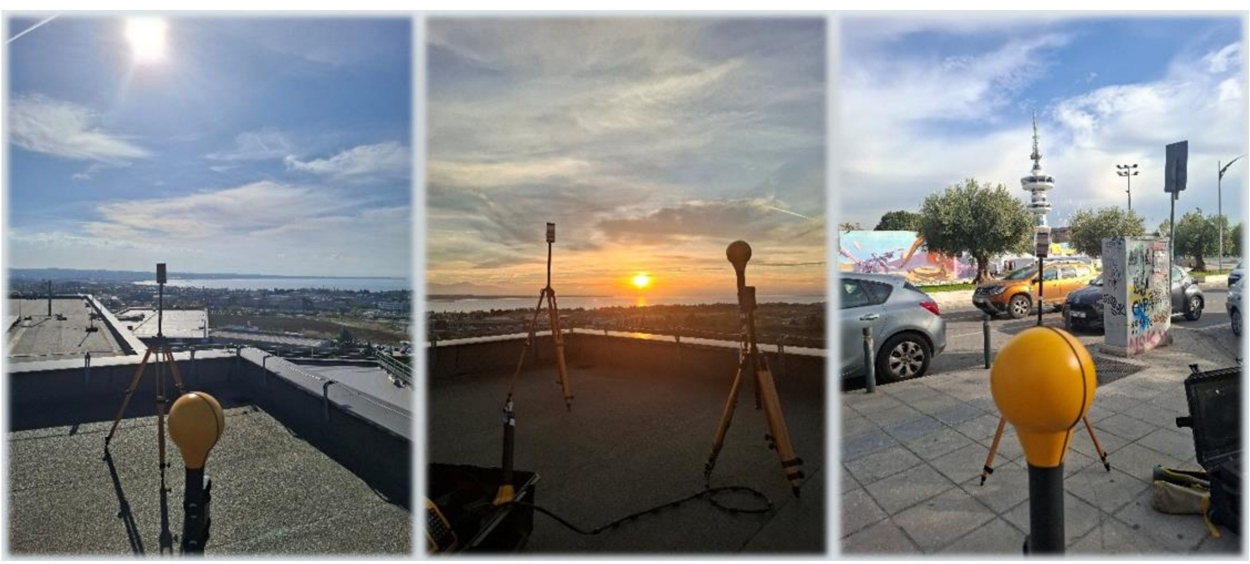

Figure 3.3. The setup for measurements performed in Thessaloniki, Greece for 5G MaMIMO exposure assessment.

3.4 Slovenia

As illustrated in Figure 3.4, the measurements conducted in Slovenia covered a mix of microenvironments, including industrial and rural sites in Ljubljana. These measurements were performed for both FTP-DL and Overview types, following the standardized settings and procedures defined in [3]. The campaign focused on a single provider within the designated spectrum frequency band of 3.42 to 3.52 GHz. At each site, a 3-point spatial averaging approach was applied across 20 measurement spots, resulting in a total of 80 measurements when considering both types.

Figure 3.4. The setup for measurements performed in Ljubljana, Slovenia for 5G MaMIMO exposure assessment.

4 Results and Observations

4.1 General

Table 4.1 shows the data provided by each participating country in this study, based on the type of the measurements performed. Note that the 9-point spatial measurements have been reused in 3-point, 6-point, and 9-point spatial averaging since they were performed sequentially. If the spectrum data is available for overview measurements from 700 to 4000 MHz, it has been reused for overview of the 5G-NR spectrum exposure.

Table 4.1. The detailed list of the measurements performed for the intercounty study on 5G-NR MaMIMO exposure.

Country	Measurement Type						
	Overview		FTP-Download / Download				SSS Block
	700 to 4000 MHz	5G-NR (3.5 GHz)	Central Point	3-Point	6-Point	9-Point	
Belgium	27*	2	26	6	2	2*	6
France	-	82	-	82	-	-	-
Greece	4	1	3	9	3	3*	-
Slovenia	20*		20	20	-	-	-

* This data has been reused partially for other types of measurement in this study.

4.2 Measurement duration

The objective of this section is to investigate the averaging duration for 5G-NR MaMIMO exposure assessment. In this analysis, the start of the averaging window is fixed at the beginning of the measurement, while the averaging-bin's length is progressively increased in 5-second increments. For each increment, the resulting averaged value is compared against the overall time-average of the full measurement period. As an example, presented in Figure 4.1, this produces several recurring patterns in the behaviour of the resulting averaging figure. The following figures illustrate a couple of the most representative categories, accompanied by an example time-series plot corresponding to the measurement under study.

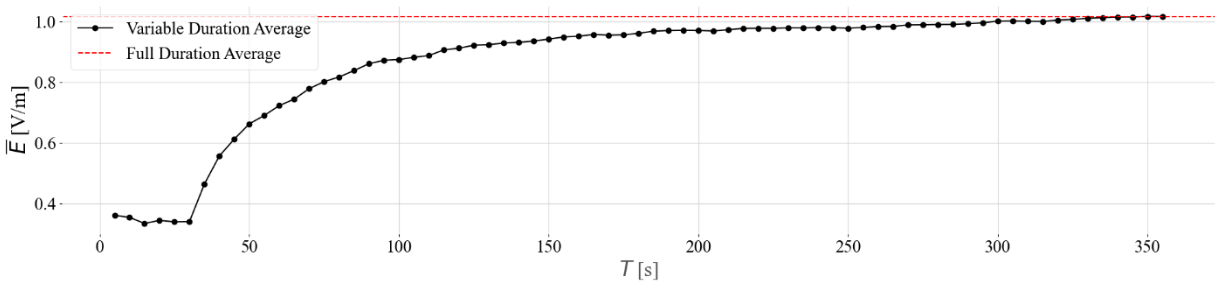

Figure 4.1. (Type 1) Variable averaging duration compared to the full-time average (vertical line) of the E-field samples over the full measurement duration of 6 minutes in an FTP-DL routine.

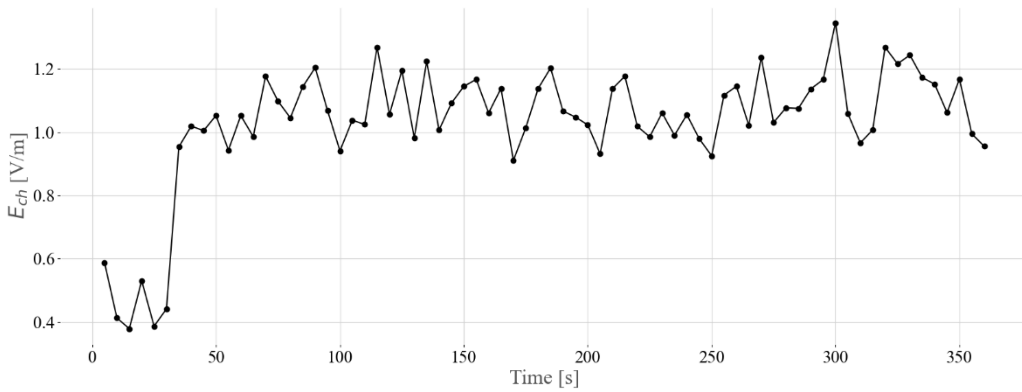

Figure 4.2. Time-series plot of the sampled channel E-field strength during a 6-minute FTP-DL measurement.

Figure 4.1 presents the comparison between the variable-duration average, computed by increasing the averaging window in 5-second increments and the full-time average of the measurement. Figure 4.2 shows the corresponding time-series of the measured channel E-field over the 6-minute measurement interval.

Figure 4.1 illustrates the first category (Type 1) observed in the duration study of the FTP-DL routine. This category is characterized by a gradual increase in the averaged value, eventually converging to the full-duration average. The most desirable case is when this convergence occurs rapidly, indicating that the controlled user terminal (UT) became active at or immediately after the start of the routine. Other variations of the same general type can exceed the full-duration average when the E-field levels drop during the measurement for example because of a link disruption.

Figure 4.3 presents a second example of the averaging-duration analysis, corresponding to Type 2. As shown in Figure 4.3 and Figure 4.4, when the controlled UT is already active before data reporting begins and a clear initial power peak or dip is present, the variable-duration average converges rapidly to the full-time average. Furthermore, the variance of the variable-duration average is reduced by roughly a factor of 20 compared to the variance in the

Type 1 example. This behaviour demonstrates that the controlled UT overwhelmingly drives the base-station resource utilization, while other time-varying environmental influences, such as user mobility or background traffic dynamics, remain comparatively stable throughout the measurement period.

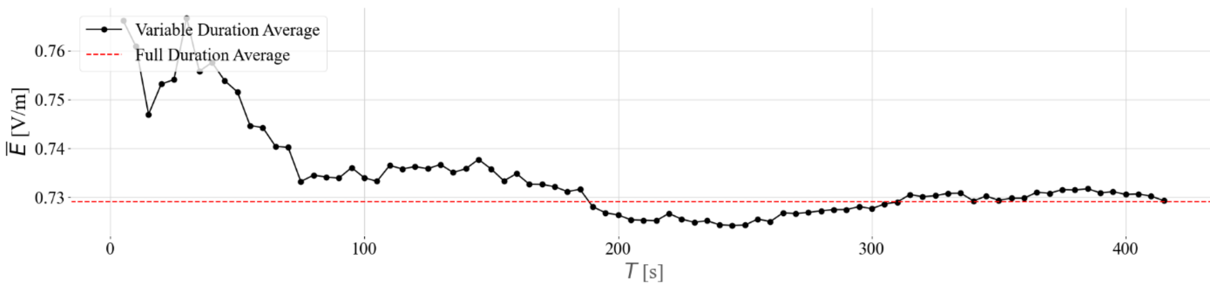

Figure 4.3. (Type 2) Variable averaging duration compared to the full-time average (vertical line) of the E-field samples over the full measurement duration of 6 minutes in an FTP-DL routine. (Data collected for up to 420 seconds.)

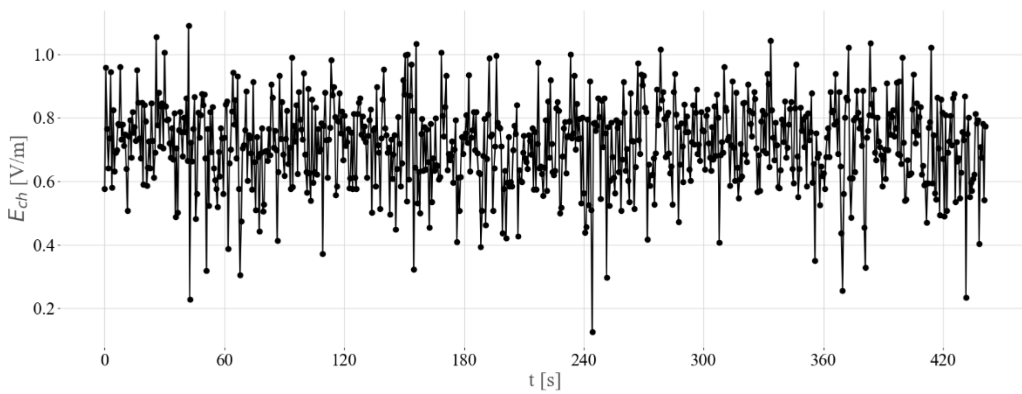

Figure 4.4. Channel E-field samples during an FTP-DL measurement.

As shown in Figure 4.3, when only the first few samples are used for evaluation, the resulting average deviates by approximately 5.5 % (< 0.04 V/m) from the full-duration average. After about 80 seconds, this deviation decreases to below 1.5 %, indicating a rapid convergence once a sufficient portion (dependant on dynamic factors) of the measurement interval is included.

According to the duration study, the variable averaging reached a deviation of less than 5% from the 6-minute reference average after an average of 46 seconds in Belgium, 55 seconds in Greece, and 34 seconds in Slovenia during download routines such as the FTP-DL routine. This suggests that even in real-world networks, the downlink exposure can be accurately evaluated at considerably shorter averaging durations than 6-min and 30-min averaging duration.

Other scenarios may involve short-term disruptions during the measurement routine. In such cases, selecting an averaging duration that is too short can lead to either overestimation or underestimation of the exposure level. These effects manifest as fluctuations around the full-time average in the duration-study curves and emphasize the importance of choosing an averaging window that is sufficiently long to smooth out transient variations in traffic load, user activity, or environmental dynamics.

When measurement results exhibit behaviour similar to Type 2, it may be possible to reduce the overall measuring duration by using a time interval derived on site for points that share similar local conditions. These conditions include, but are not limited to, the number of scatterers near the evaluation point, the level of user activity, the number of users present, the dynamism of the surroundings, and the acceptable deviation from the full-time measurement results.

4.3 Overview measurements

Figure 4.5 shows the 6-minute average E-field strength for the overview measurements conducted across several European countries in the 5G-NR MaMIMO spectrum. The overview measurements in the band from 700 to 4000 MHz has been reused to extract 5G-NR spectrum data for Figure 4.5. The results indicate that Slovenia and France exhibit the highest peak values, ranging from approximately 1.2 V/m to 1.5 V/m. These two countries also show a substantially larger (3 to 4 times) interquartile range compared to Belgium, suggesting greater variability in the measured exposure levels.

The median values reveal similarities between Belgium and France, whereas Slovenia shows a noticeably higher median at approximately 0.125 V/m above the others.

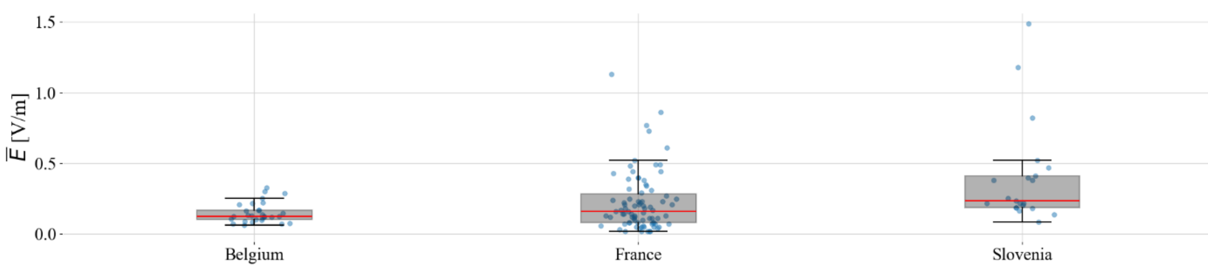

Figure 4.5. 6-minute average for overview measurements performed in the participating European countries for 5G-NR MaMIMO exposure assessment on E-field strength.

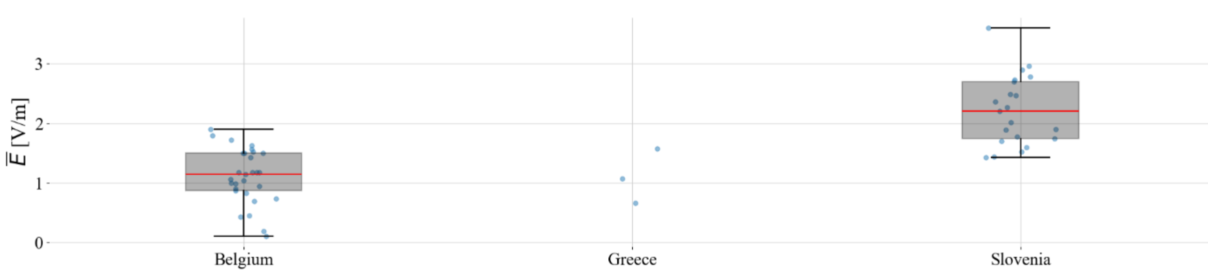

Figure 4.6. 6-minute average for Overview measurements performed in the participating European countries for the spectrum from 700 to 4000 MHz on E-field strength.

4.4 FTP-DL measurements

Figure 4.7 shows the 6-minute average E-field strength for the FTP-DL measurements conducted across the participating countries in the 5G MaMIMO spectrum. The 3-point averaging measurements from France have been reused to generate Figure 4.7. The results indicate that France exhibits the highest peak values from 6 V/m to 9 V/m, which is almost 55% higher than Slovenia's peak, the second country in terms of peak exposure. These two countries also show a substantially larger (3 to 5 times) interquartile range compared to Belgium and Greece, suggesting greater variability in the measured exposure levels.

The median values reveal that exposure levels in Belgium, Greece, and France are in the same bin from 0 V/m to 2 V/m, whereas Slovenia shows a noticeably higher median in the 2 V/m to 4 V/m. Additionally, a noticeable portion of the recordings from France also fall into the 2 V/m to 6 V/m range.

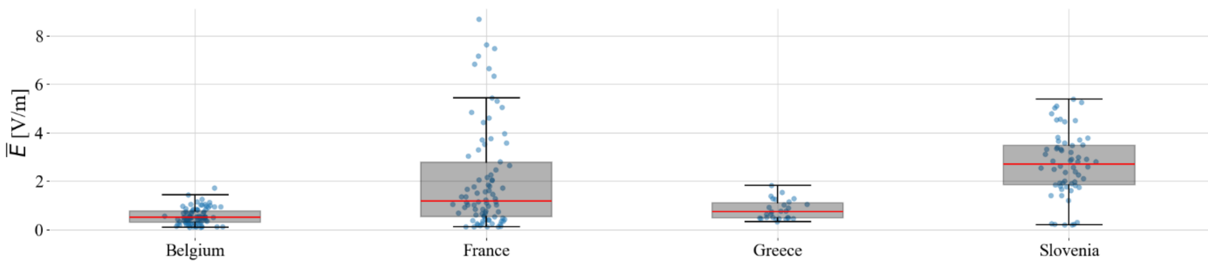

Figure 4.7. 6-minute average FTP-DL measurements performed in four participating European countries for 5G-NR MaMIMO exposure assessment on E-field strength.

4.5 SSS Measurement

Figure 4.8 compares extrapolated SSS E-field results with actual maximum exposure from FTP-DL measurements, where the median per EP serves as the reference. The extrapolation considers the ratio of the total carrier bandwidth to subcarrier frequency spacing of SSB (F_{BW} = 3276 = 12×273), the power reduction for actual maximum approach (F_{PR} = 1), the technology duty cycle (F_{TDC} = 75%), and transmitted power ratio of broadcast to traffic beam (F_B = 1). Repeated SSS-based measurements exhibit negligible variation across EPs. The 2-min code-selective averages of broadcast beams range from 25.5 mV/m at EP1 to 6.7 mV/m at EP6. The mean absolute error of 8.5-10.3 dB across EPs quantifies the difference between the assumed extrapolation factors and real-world maximum exposure.

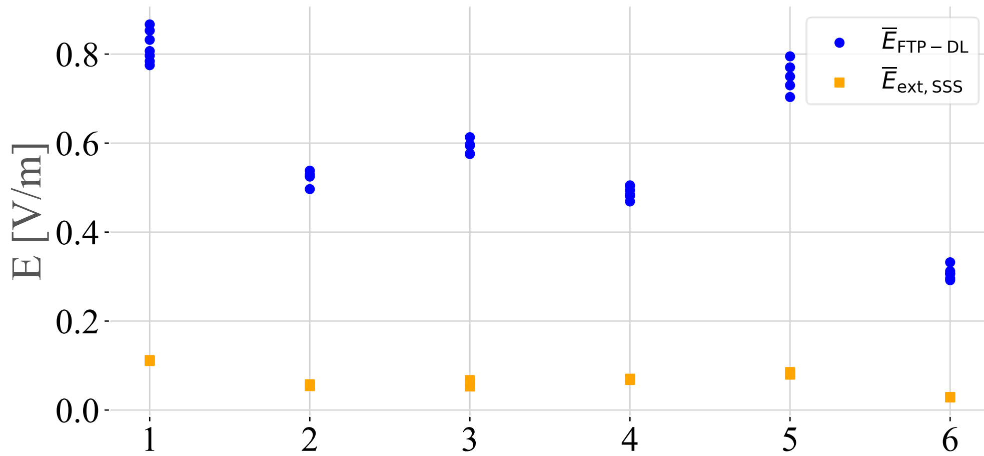

Figure 4.8. E-field strength comparison between the partial extrapolation (without *FB* factor) of the broadcast beam and the FTP-DL measurements across EPs. Measured values were averaged over 2-min for broadcast beam and over 6-min for the FTP-DL routine.

4.6 Peak-to-Average Ratio

Figure 4.9 presents the peak-to-average ratio (PAR) for E-field strength of the FTP-DL measurements conducted across the participating European countries in the 5G-NR MaMIMO spectrum. The results indicate that Slovenia is reporting the largest PAR values. The PAR conservatively stays in the range from 1 to 4 for all three countries with a few points outside of this range that can be explained by low averages, high peaks or a combination of them.

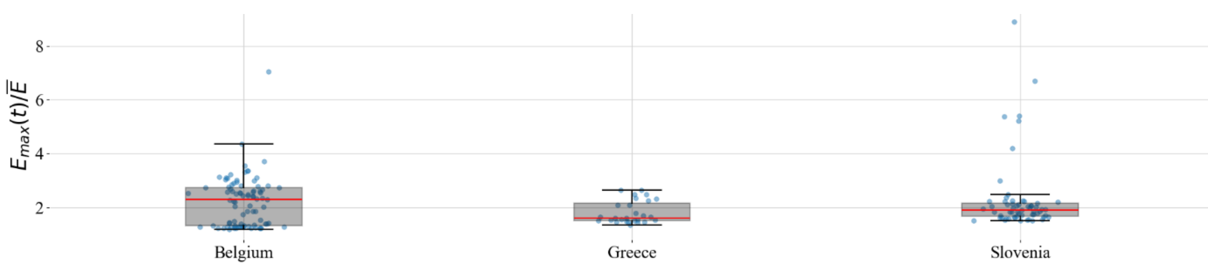

Figure 4.9. Peak-to-Average ratio comparison between the participating European countries for 5G MaMIMO exposure assessment on E-field strength.

4.7 Spatial averaging

For spatial averaging the data collected in Belgium and Greece were used since 9-point measurements were performed for a limited number of evaluation points. Figure 4.10 shows the comparison of spatial averaging with different number of sampling points compared to the central point for measurements performed in Belgium and Greece. The data from 9-point measurements has been reused for the other spatial averaging methods. The results show that typically the central point measurements estimated a minimum for the exposure and different spatial averaging estimates showed a 5 to 10 percent higher exposure level. This is mainly due to the multipath effect where points at different heights can receive a varied signal strength depending on their location. For example, in Greece mostly the points at 1.1 or 1.5 meters have a higher exposure, yet in Belgium, the points at 1.5 or 1.7 meters are dominant for the selected EPs.

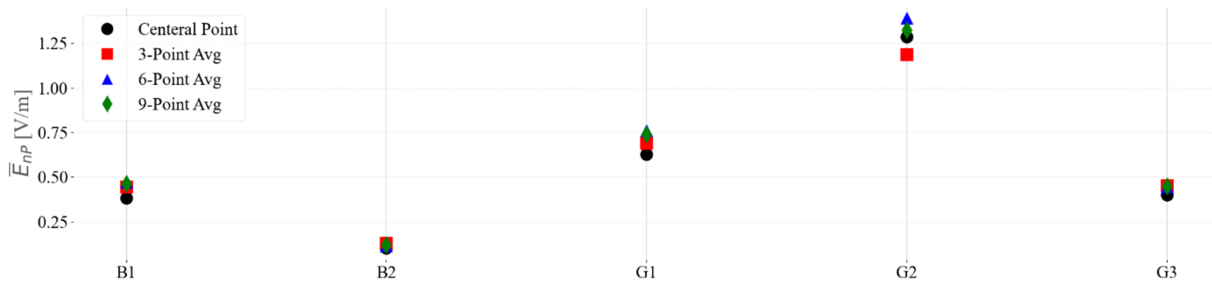

Figure 4.10. Comparison of the spatial averaging for 3, 6, and 9 points against the central point measurements of e-field strength in V/m.

The 3-point spatial averaging proved to be of sufficient accuracy with a mean absolute error of 0.6 % and 4.51 % in Belgium and Greece, respectively. Thus, the 3-point spatial averaging is sufficient for the intercountry comparison. Figure 4.11 provides the 3-point spatial average of 5G-NR MaMIMO spectrum between all of the participating countries.

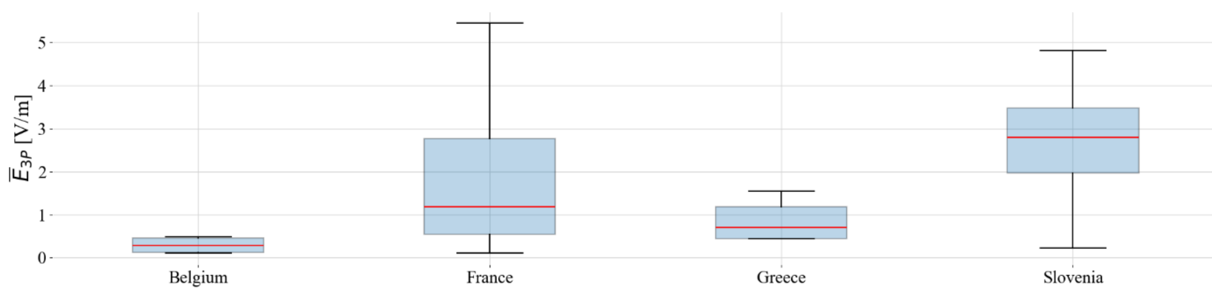

Figure 4.11. Comparison of the 3-point spatial averaging for the participating European countries for measurements of e-field strength.

The results in Figure 4.11 are similar to Figure 4.7 as expected, showing that for a general estimation of exposure the central point and the 3-point spatial averaging measurements are of sufficient accuracy.

5 Conclusions and Recommendations

The averaging duration study showed that a shorter averaging duration is possible in 5G-NR assessment in real-world networks since a deviation of less than 5% was observed by average after 46 seconds in Belgium, 56 seconds in Greece and 34 seconds in Slovenia from a 6-min average.

The elevated median, combined with the broader spread of the data during overview and FTP-DL measurements, indicate more pronounced fluctuations and generally higher exposure conditions in the Slovenian measurements. As expected, this results also in the highest peak-to-average ratios in the reported data. Additionally, during the FTP-DL measurement in France the highest peaks were reported at a range of 6 V/m to 9 V/m. Note that all evaluation points were deliberately selected to represent a worst-case scenario expected in a real-world network.

The SSS-based extrapolation for maximum exposure estimation in Belgium revealed that the typical extrapolation factors used, underestimate the difference of exposure between the broadcast beam and the traffic beam by a factor of 8.5 to 10.3 dB for the specific site selected in Belgium. This range is larger than typical maximum difference of up to 6 dB. [3]

The analysis of the spatial-averaging data shows that applying 3-point spatial average results in less than a 5% deviation from the electric-field level measured at the central point. This demonstrates that higher-order spatial averaging is generally unnecessary, unless required for specific measurement protocols.

6 References

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