



Project: **SEAWave**

Measurements in Industry 4.0 scenarios

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Abstract

5G private mobile networks are emerging as a platform for “wire-free” connectivity in professional applications across smart industry sectors such as automated warehousing, logistics, autonomous vehicle deployments in campus environments, mining, material processing, and more. It is expected that most Machine-to-Machine (M2M) and Industrial Internet of Things (IIoT) communication paths will increasingly rely on wireless solutions, as the flexibility they provide offers clear advantages over hard-wired network installations.

However, the deployment of private 5G networks in smart industries has been delayed due to a combination of high costs, technical challenges, and uncertain returns on investment, resulting in limited access to fully operational private networks.

To gain insights into workers exposure to radiofrequency electromagnetic fields (RF EMF) emitted by 5G private mobile networks, an analysis was conducted on RF EMF levels from various 5G and Wi-Fi 6 equipment in real-world scenarios across different smart industrial sectors and R&D platforms. Several exposure scenarios were evaluated, including production facilities, logistics operations, office environments, and research sites. The installations included different setups: private standalone and non-standalone 5G networks operating at 3.5 GHz and 26 GHz, as well as public networks with private slices.

The results of extensive in-situ RF EMF measurements of private 5G networks in smart industries clearly demonstrated that worker exposure levels in all investigated scenarios were well below existing exposure limits.

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1 Introduction

The need to assess Radiofrequency Electromagnetic Field (RF EMF) exposure of workers in Industry 4.0 environments arises from the unprecedented integration of wireless, automated, and interconnected technologies that generate complex, multi-frequency electromagnetic environments. Wireless communication is a cornerstone of Industry 4.0, as it enables seamless, pervasive, and scalable connectivity among machines, sensors, and mobile entities such as robots, automated guided vehicles (AGVs), drones, and humans [1].

The deployment of private 5G networks in smart industrial environments introduces unique RF EMF exposure scenarios for workers. In general, two main types of 5G equipment are used to achieve reliable coverage inside smart factories: (i) a limited number of beamforming base stations (BSs), which can cover large areas, and (ii) multiple low-power radio heads, which provide robust coverage even in environments with many obstacles and reflections. The main distinction between these devices lies in their radiation patterns and antenna gains. Beamforming antennas typically have high maximum gains (15–23 dBi) and the ability to steer beams dynamically, whereas low-power radio heads usually employ omnidirectional or partially directive radiation patterns with low gains (0–4 dBi).

Since the total maximum output power is usually similar (up to several watts), these differences result in markedly different exposure scenarios near the source: close to beamforming antennas, exposures may be several orders of magnitude higher.

The benefit of high-gain beamforming antennas is limited by the presence of obstacles, whereas multiple low-power radio heads benefit from the ability to cover the majority of the area due to their distribution throughout the building with a high percentage of clutter.

Research on workers' RF EMF exposure in fully operational private 5G networks in Industry 4.0 is still scarce. A key reason is the relatively slow adoption of private 5G in smart industries, due to high costs, technical challenges, and uncertain return on investment. Moreover, researchers' access to industrial sites equipped with private 5G networks is highly restricted. Facility owners rarely grant permission for external measurements or publication of results, and access often requires lengthy negotiations and Non-Disclosure Agreements (NDAs), which are frequently canceled by company management before completion.

Some published studies report that, while 5G beamforming concentrates energy toward intended receivers, the dynamic nature of beam patterns and time-averaged power allocation reduces overall worker exposure compared to static sector antennas. In controlled scenarios, power density often remained below 1% of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline limits [2].

2 RF EMF measurements

For RF EMF measurements, the widely applied standard is IEC 62232:2022 [3]. This standard specifies techniques and instrumentation for measuring RF EMF in both the near and far fields of sources operating in the frequency range 100 kHz to 300 GHz. It defines methodologies for three types of assessments:

- **Product compliance,**
- **Product installation compliance,**
- **In-situ RF exposure assessment.**

Although the assessment objectives differ, the evaluation methods remain the same. Two main approaches are defined:

- **Measurement methods,**
- **Computation methods.**

Measurement methods are further subdivided into:

- **SAR (Specific Absorption Rate) measurements,** and
- **RF field strength and power density measurements,** which may be conducted either:
 - **in situ,** or
 - **in the laboratory.**

For this study, **in-situ measurements** were applied. To ensure accuracy, it is essential to obtain data and technical specifications of the RF EMF sources. Such information is required both to estimate the expected EMF strength and to select the most appropriate measurement approach using properly calibrated equipment.

When determining the measurement location and method, the following parameters must be considered:

- operating frequency,
- transmission power,
- polarization,
- modulation scheme,
- pulse width and repetition frequency,
- antenna characteristics (gain, beamwidth, radiation pattern, etc.).

To determine the RF EMF strength, we need to know:

- distance from the source,
- presence of reflective objects that can increase the electric field strength by a factor of 2.

In general, in the near field, both the electric field E and magnetic field H must be measured, however in practice it is usually enough to measure the one that is higher in absolute value. In far field, it is enough to measure only E or H , as they are related to each other through the

impedance of free space. In practice for frequencies up to 30 MHz the H field is usually measured, and E field for higher frequencies.

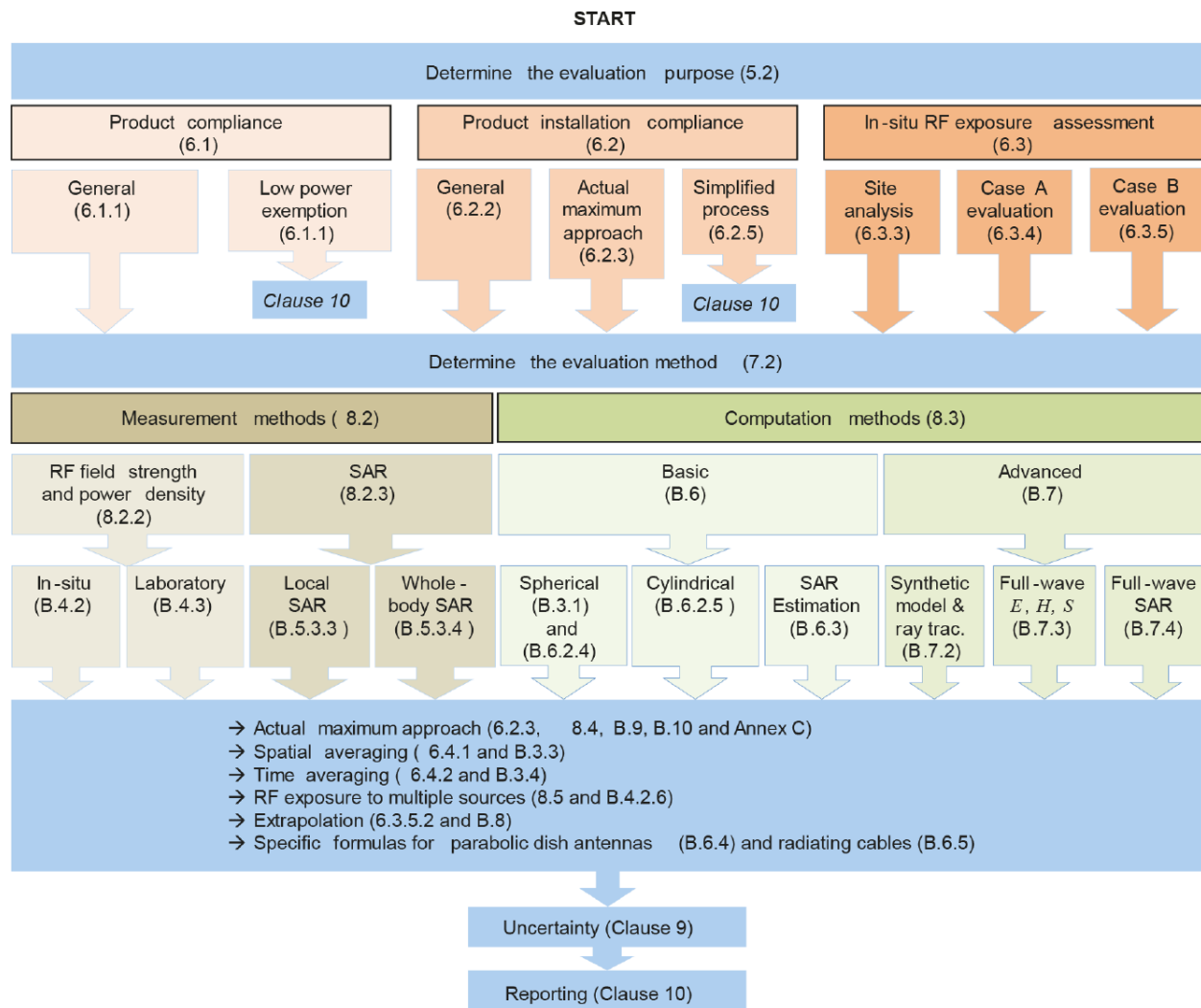


Figure 1. Evaluation process for product compliance, product installation compliance and in-situ RF exposure assessment (IEC 62232:2022 [3])

When performing measurements of base stations, it is necessary to determine maximum values. Standard IEC 62232:2022 [3] in chapter 6.3.5.2. foresees three options for determining maximum values, including:

1. measurements under load (IEC 62232:2022 [3] chapter B.4.2.5.4),
2. broadband measurements and extrapolation (IEC 62232:2022 [3] chapter B.8.2) and
3. frequency or code selective measurements and extrapolation IEC 62232:2022 [3] chapter B.8.3).

The second option, broadband measurements and extrapolation are limited by several factors, like any presence of other sources, higher uncertainty, lack of any possibility to distinguish the contributions of different antennas, no possibility to check the working conditions of equipment under test... Therefore, the second option will normally not be used.

A 3-axis quasi-isotropic antenna can be used for measurements. This ensures that the radio signals are captured regardless of their direction of incidence and polarization. If quasi-isotropic antennas cannot be used, special care must be taken during the measurements to ensure that the maximum values at the measurement location are measured.

It is also assumed that the effect of field strength variations within a small space is considered using the sweeping method. This implies that the maxima of the fields present within the measurement space that are used as the basis for the exposure evaluation are obtained in practice by moving the measuring antenna slowly within the space.

2.1 Measurements under load

Measurements underload can be used when it is possible to ensure that during the measurements the equipment under test is operating at maximum power. This can be achieved either by a speed test or by setting the equipment under test in specific mode when it is transmitted at maximum power.

Speed tests can be used when there is only one source present nearby so that when performing speed test, we are guaranteed that the device generating the traffic is the one under test. The benefit of measurements under load by speed test is that they can be performed independently from the owner of the source with the minimal technical data necessary to perform the measurements and very little post processing of measured data. If there are multiple sources available, it is possible to perform measurements with speed test if only the device under test is operational and other sources are either switched off or operate in a different frequency band. However, for live networks this option is usually not liked by network providers.

Measurements when the source is operating in specific mode at maximum power is the only possibility to measure the source at maximum power if multiple sources are present at a location. However, to establish such a specific working condition of the equipment under test, a close collaboration with network provider is necessary.

2.2 Selective measurements

2.2.1 Selective measurements of 4G networks

Code-selective measurements of the E field of 4G base stations are performed by the use of specific 4G demodulator to measure the RF RMF of the reference signal (RS). Since 4G BS can have wider frequency bandwidth (up to 20 MHz) using a spectrum analyzer with an RBW of 20 MHz is appropriate.

Extrapolation to maximum values can be done with the instrument that decodes and measures the amplitude of the reference signal RS, which has a constant power with a tolerance of less than 0.5 dB. However, the input data are necessary: 4G channel central frequency, cell identification code (ID), 4G channel width (CBW), RS reference signal strength and the maximum or permitted output power of the 4G cell.

The extrapolation to maximum E field is calculated according to the formula (IEC 62232:2022 [3] chapter E.7.5.2 and F.8.4.1):

$$E_{max} = \sqrt{\frac{n_{RS}}{BF} \times F_{TDC} E_{RS}^2}$$

$$n_{RS} = \frac{P_{max}}{P_{RS}}$$

where

- E_{max} - the maximum value of E field for individual 4G BS cell,
- n_{RS} – ratio between the maximum permitted transmission power and the RS power,
- E_{RS} – measured E field of RS,
- P_{RS} – RS power, information is provided by service provider,
- BF – boosting factor for the RS, information is provided by service provider,
- F_{TDC} – TDD duty cycle,
- P_{max} – maximum transmit power of the cell; information is provided by service provider.

If code-selective equipment is not available, it is possible to perform spectrum-selective measurements to determine the PBCH power.

The procedure for frequency-selective measurements of an LTE signal is (IEC 62232:2022 [3] chapter E.7.5.3):

- set spectrum analyzer to zero span mode.
- set the center frequency of the spectrum analyzer to the center frequency of the LTE signal.
- set resolution bandwidth (RBW) to 1 MHz.
- set sweep time to approximately the product of the number of display points of the SA and the symbol duration (approximately 70 μ s), e.g. a sweep time of approximately 70 ms for an SA with 1 000 display points.
- set detector to RMS.
- set VBW to RBW or greater or switch it off.
- set to max hold.
- measure for at least 20 s.

The extrapolation to maximum E field is calculated according to the formula (IEC 62232:2022 [3] chapter E.7.5.3):

$$E_{max} = \sqrt{\frac{n_{PBCH}}{BF}} \times F_{TDC} E_{PBCH},$$

$$n_{PBCH} = \frac{N_{RS}}{72}$$

where

- E_{max} - the maximum value of E field for individual 4G BS cell,
- n_{PBCH} – ratio between the maximum permitted transmission power and the transmission power corresponding to the PBCH over six RBs,
- E_{PBCH} – measured E field of PBCH,
- N_{RS} – number of subcarriers in the used transmission bandwidth (see Table 1),
- BF – boosting factor for the RS, information is provided by service provider,
- F_{TDC} – TDD duty cycle.

n_{PBCH} is the extrapolation factor for the PBCH, which is the ratio of the maximum transmission power to the transmission power corresponding to the PBCH over six RBs. n_{PBCH} can be provided by the network operator or can be calculated theoretically.

Table 1: Extrapolation factor N_{RS} (IEC 62232:2022 [3] chapter E.7.5.2 Table E.10).

Channel bandwidth [MHz]	Number of resources	Transmission bandwidth [MHz]	N_{RS} = extrapolation factor for RS
1.4	6	1.08	72
3	15	2.7	180
5	25	4.5	300
10	50	9	600
15	75	13.5	900
20	100	18	1200

However, the frequency-selective measurement cannot identify the signal of each LTE cell due to frequency spectrum overlapping. Therefore, frequency-selective measurements and extrapolation is possible only when it is known that the PBCH power is predominantly emitted by one LTE cell.

2.2.2 Selective measurements of 5G networks

Maximum value for the 5G NR base station without beamforming is determined using a code-selective instrument that decodes and measures the amplitude of the SSS (Secondary Synchronization Signal) signal, which has a constant power. The necessary input data are: center frequency of the SSS signal (can be different from the center frequency of the NR channel), cell

identification code (ID), SSB bandwidth (SSB), NR channel bandwidth (CBW), SSS power and maximum NR Tx power.

The extrapolation to maximum E field is calculated according to the formula (IEC 62232:2022 [3] chapter E.8.2.1.2):

$$E_{max} = \sqrt{\frac{n_{RE,SSS} \times F_{TDC}}{BF}} E_{RE,SSS},$$

$$n_{RE,SSS} = \frac{P_{max}}{P_{RE,SSS}}.$$

where

- E_{max} - the maximum value of E field for individual 5G BS cell,
- $n_{RE,SSS}$ – ratio between the maximum permitted transmission power and RE power,
- $P_{RE,SSS}$ – RE power, information is provided by service provider,
- P_{max} – maximum transmit power of the cell, information is provided by service provider,
- F_{TDC} – TDD duty cycle.
- BF – boosting factor for the RS, information is provided by service provider,
- $E_{RE,SSS}$ – Measured RE power in SSS.

$n_{RE,SSS}$ is determined by the signal bandwidth and subcarrier spacing - SCS. The values are provided in Table 2 and Table 3.

Table 2: Extrapolation factor $n_{RE,SSS}$ for frequencies below 6 GHz (IEC 62232:2022 [3] chapter E.8.2.1.2 Table E.11).

SCS [kHz]	Bandwidth [MHz]												
	5	10	15	20	25	30	40	50	60	70	80	90	100
15	300	624	948	1272	1596	1920	2592	3240	n/a*	n/a*	n/a*	n/a*	n/a*
30	132	288	456	612	780	936	1272	1596	1944	2268	2604	2940	3276
60	n/a*	132	216	288	372	456	612	780	948	1116	1284	1452	1620

Table 3: Extrapolation factor $n_{RE,SSS}$ for frequencies above 6 GHz (IEC 62232:2022 [3] chapter E.8.2.1.2 Table E.12).

SCS [kHz]	Bandwidth [MHz]			
	50	100	200	400
60	792	1584	3168	n/a*
120	384	792	1584	3168

If code-selective equipment is not available, it is possible to perform spectrum-selective measurements to determine the E_{SSB} , which is electric field per resource element of the strongest measured SSB beam. As the SSB is spread in time, when performing spectrum selective

measurement, it is impossible to measure the power of the RE SSB directly, but it requires post processing of measured data to identify the resources allocated to the SSB.

Procedure for frequency selective measurements of 5G signal is (IEC 62232:2022 [3] chapter E.8.2.1.3):

- set spectrum analyzer to zero span mode;
- set the center frequency of the spectrum analyzer to the center frequency of the SSB;
- set resolution bandwidth (RBW) to less than 127 sub-carriers (1 MHz);
- set sweep time to approximately the product of the number of display points of the SA and the symbol duration;
- set detector to RMS;
- set VBW to RBW or greater or switch it off;
- set to max hold;
- measure for at least 20 s.

A factor of $\sqrt{\frac{SCS}{RBW}}$ should be applied to the measured value to obtain the RF field strength per RE. The extrapolation to maximum E field is calculated the same way as for code-selective measurements.

2.2.3 Selective measurements of 5G networks using beamforming

Measurements of a base 5G NR base station with beamforming are performed in the same way as measurements of a 5G NR base station without beamforming. When calculating the maximum value, an additional factor must be considered due to the differences in the radiation patterns of the antenna when transmitting the SSS signal (pilot) and the PDSCH signal (traffic) (IEC 62232:2022 [3] chapter E.8.2.1.4):

$$E_{max} = \sqrt{\frac{n_{RE,SSS} \times F_{TDC} \times F_{ant}(\varphi, \theta)}{BF}} E_{RE,SSS},$$

$$n_{RE,SSS} = \frac{P_{max}}{P_{RE,SSS}}$$

where

- E_{max} - the maximum value of E field for individual 5G BS cell,
- $n_{RE,SSS}$ – ratio between the maximum permitted transmission power and RE power,
- $P_{RE,SSS}$ – RE power, information is provided by service provider,
- P_{max} – maximum transmit power of the cell, information is provided by service provider,
- F_{TDC} – TDD duty cycle,
- F_{ant} – beamforming factor due to different antenna gains when transmitting SSS signal and PDSCH signal (1 if there is no beamforming),
- BF – boosting factor for the RS, information is provided by service provider,
- $E_{RE,SSS}$ – measured RE power in SSS.

Beamforming factor F_{ant} is calculated according to:

$$F_{ant} = 10^{\frac{(G_{PDSCH} - At_{PDSCH}) - (G_{SSS} - At_{SSS})}{10}} = 10^{\frac{(G_{PDSCH} - G_{SSS}) + (At_{SSS} - At_{PDSCH})}{10}}$$

where:

- G_{PDSCH} - antenna gain when transmitting PDSCH signal (in dB),
- At_{PDSCH} - envelope of relative attenuation of antenna when transmitting PDSCH signal in the direction of evaluation (measurement location) (in dB),
- G_{SSS} - antenna gain when transmitting SSS signal (in dB),
- At_{SSS} - envelope of relative attenuation of antenna when transmitting SSS signal in the direction of evaluation (measurement location) (in dB).

Both relative attenuations are dependent on the azimuth and elevation from the antenna to the measurement location. However, if the measurement location is outside of the envelope of the main beam of SSS signal, the ratio between At_{SSS} and At_{PDSCH} can be very high, which leads to great overestimations of the extrapolated maximum value. Standard IEC 62232:2022 [3] does not address this issue, the only available proposal is the document published by Swiss Federal Office for Environment [4], which is as follows:

1. if in main beam ($At_{SSS} < 20$ dB):
 - a. if $At_{SSS} \leq At_{PDSCH}$, then $At_{SSS} - At_{PDSCH} = 0$ dB;
 - b. if $At_{SSS} > At_{PDSCH}$, then $At_{SSS} - At_{PDSCH} = At_{SSS} - At_{PDSCH}$;
2. if out of main beam ($At_{SSS} \geq 20$ dB): $At_{SSS} - At_{PDSCH} = \max((At_{SSS} - At_{PDSCH})$ where $At_{SSS} < 20$ dB).

In case 1.a and sometimes in case 2 this method overestimates the exposure compared to method from IEC 62232:2022 [3]. In [5] they showed that extrapolation of the measured $E_{RE,SSS}$ to maximum value E_{max} is quite conservative approach. Thus, it is of no interest to further overestimate the exposure. Therefore, slightly modified above-described method of BAFU will be used:

1. if in main beam ($At_{SSS} < 20$ dB): $At_{SSS} - At_{PDSCH} = At_{SSS} - At_{PDSCH}$
2. if out of main beam ($At_{SSS} \geq 20$ dB): $At_{SSS} - At_{PDSCH} = \min(At_{SSS} - At_{PDSCH}, \max((At_{SSS} - At_{PDSCH})$ where $At_{SSS} < 20$ dB)).

2.3 Measurements of Wi-Fi 6 networks

Due to the intermittent and non-continuous nature of Wi-Fi transmissions, spectrum analyzers often miss signal bursts or record incomplete traces. Limitations in sweep time and resolution bandwidth prevent accurate capture of the full emitted power in real time. Therefore, peak measurements should be used to reliably capture transmission bursts, followed by the application of a separately estimated duty-cycle factor to calculate the time-averaged exposure.

The step-by-step procedure for conducting exposure measurements of Wi-Fi signals using a spectrum analyzer is the following (IEC 62232:2022 [3], chapter E.6.5):

- identify active channels,
- set the spectrum analyzer span to cover the active channel,
- set the value of the spectrum analyzer's resolution bandwidth large enough so the sweep time does not exceed 1 second,
- set the spectrum analyzer to peak/max hold mode,
- record until the peak level stabilizes,
- convert spectral components to RF field strength,
- remove noise by zeroing spectral components below twice the baseline noise level interpolated just outside of the Wi-Fi channel,
- integrate the result to determine power density,
- *measure or estimate and apply the duty-cycle factor.*

The integrated power density is calculated from the spectral components:

$$S_{int} = \frac{\Delta f}{1.055 \cdot RBW} \cdot \sum_i S_i$$

where:

- S_{int} is the integrated power density of the Wi-Fi signal,
- Δf is the frequency spacing between the stored spectral components, typically $RBW/2$,
- RBW is the resolution bandwidth of the spectrum analyzer during the measurement,
- S_i is the power density of the i th measured spectral component after the noise has been removed.

The integrated power density S_{int} can be used to assess the maximum exposure. For the actual exposure its value must be multiplied by the duty cycle factor, T_{DC} . The duty cycle factor can be determined by conducting zero span measurements with the spectrum analyzer, setting its center frequency to that of the active Wi-Fi channel and measuring the active duration and the total duration of the Wi-Fi signal. The duty cycle can also be estimated with the use of network analyzer tools.

2.4 Measurements of M2M and IOT in private networks

When measuring RF EMF emitted by different M2M and IOT devices in private networks, it is usually much harder to determine the exact working conditions during the measurements. In real situations when the devices are working normally, there are limited possibilities to influence the traffic of these devices.

Therefore, measurements of M2M and IOT devices in private networks should be performed when there is possibility to either determine the working conditions of equipment under test during the measurements or when there is possibility to establish full load during measurements.

3 Measurement protocol

3.1 Intention of measurements

Measurements will be used to:

1. validate the model predictions and
2. determine the real exposures of workers due to private mobile networks from both the infrastructure sources such as macro and micro base stations and from user equipment devices.

According to IEC 62232:2022 [3] standard, there are no special measurement procedures for 5G industrial networks, therefore general measurement procedures described in IEC 62232:2022 [3] will be used for such systems.

3.2 Gathering the data

Before the measurement takes place, the technical data of the used system should be obtained to prepare the measurement strategy and simulation. Important data that must be obtained are:

- Location description
 - type of location
 - type of installation
- Physical antenna parameters
 - type of antenna
 - location of antenna
 - antenna height
 - antenna orientation
 - azimuth
 - downtilt
- Electrical antenna parameters
 - electronic downtilt
 - envelope of radiation patterns in use
 - for beamforming antennas: envelope of radiation patterns for pilot signal
- Cell parameters
 - source type
 - frequency
 - bandwidth
 - MIMO configuration
 - max output power
 - for TDD: duty cycle or UL:DL ratio
 - power of pilot signal
 - cable and other losses
 - channel number (UARFCN/EARFCN/NARFCN)
 - PCI - Physical Cell ID
 - for 5G NARFCN of pilot channel
 - for 5G: subcarrier spacing (SCS)

3.3 Selection of measurement equipment

At measurement locations, first the spectrum scan should be done to confirm the consistency of the data (frequency, bandwidth...) and the presence or absence of interfering signals.

The measurements should be carried out with the spectrum analyzer. In conditions where no other EMF sources that could significantly influence the measurement are present, it is also possible to carry out measurements with wideband instruments with appropriate probe.

3.4 Measurement height

Where relevant, the measurement height should be 1.5 m above ground if not specified differently by the detailed protocol. For all measurement locations, the distance (vertical and horizontal) from the antenna should be determined. The situation should also be recorded (sketched), so simulation and comparison with the measurements is possible afterwards.

3.5 Load conditions

At all measurement locations, measurement of maximum values (worst case scenario) should be performed. To perform measurements of maximum value, we suggest the presence of the system operator who can ensure full transmission power (e.g. Speed test mode App) or this can be done by code- or frequency-selective measurements of pilot signals and later extrapolation for worst case scenario.

Further, to determine the real exposures of workers due to private mobile networks, average values during the transmission, and typical values in normal operating conditions should be measured if possible.

3.6 Scenarios of the measurements

To address all three scenarios of the measurements as described in chapter 3.1 *Intention of measurements*, we propose three types of measurements:

- Ad 1.: line EMF measurements in the vicinity of the antenna (compliance boundary and validation);
- Ad 2.: raster EMF measurements (validation) and
- Ad 3.: EMF measurements at workplaces (workers exposure).

Details about each type of measurement are given below.

3.6.1 Line measurements in the vicinity of the antenna (compliance boundary and validation)

Line EMF measurements conducted near antennas are primarily intended to determine the compliance zone of the source and to validate propagation models. These measurements apply both to infrastructure (base stations) and to user equipment, such as M2M and IoT devices, and should be carried out separately for each source. They must be performed either as selective measurements identifying the worst-case exposure or under full-load operating conditions.

Measurements should be taken in different directions and at varying distances from the antenna.

For infrastructure (base stations)

- **At 1.5 m above ground level:**
 - In the direction of the main beam,
 - 45° to the left or right of the main beam,
 - 90° to the left or right of the main beam.
- **At the height of the main beam:**
 - In the direction of the main beam,
 - 45° to the left or right of the main beam,
 - 90° to the left or right of the main beam.
- **Below the antenna.**

Due to installation height and surrounding obstacles, it is often not possible to perform measurements in all directions or at all heights listed above.

For user equipment (M2M and IoT devices)

The directions should be chosen based on the radiation characteristics of the equipment under test. As most user devices have a quasi-omnidirectional or weakly focused radiation pattern, directionality is generally less critical. However, it is recommended to consider at least two directions, one of which should correspond to the maximum emission values.

Measurement distances

Measurements should be taken at 0.2 m, 0.5 m, 1 m, 2 m, 5 m, 10 m, 20 m, and 50 m from the antenna. As with directions, installation height and environmental constraints often make it impractical to measure at all specified distances. Measurements may also be limited to distances where exposure levels fall below the EU recommended limits for the general public. This is particularly relevant for user equipment, as exposure values are typically already very low at 0.2 m, making further measurements unnecessary.

Time variability of exposure

To assess time variability, time-controlled measurements should be performed at one representative location. Such measurements should span at least 6 minutes, with EMF values recorded every few seconds. This allows calculation of various averaging periods and provides data for analyzing the most appropriate averaging interval for 5G exposure assessment.

Documentation of conditions

All relevant factors for numerical modeling should be documented during measurements. This includes:

- Technical specifications of the sources,
- Location and position of the sources,

- Operating conditions,
- Environmental factors,
- Surrounding objects that could influence RF EMF propagation (e.g., dimensions of indoor spaces, nearby outdoor structures, building materials, floor layout).

3.6.2 Raster EMF measurements (validation)

Measurements are carried out at a height of 1.5 m across the entire targeted area using a 10 m raster grid. The targeted area is defined as either the building (or part of the building) where the indoor base station is installed, or, in the case of outdoor installations, the area where exposure exceeds the EU recommendation limits for the general public. These measurements focus exclusively on infrastructure (base stations).

They must be performed either as code- or frequency-selective measurements, with determination of worst-case exposure under full load conditions, or as direct measurements during full load operation.

During measurements, all factors relevant for numerical modeling should be documented. This includes: complete technical data on the sources, their location and orientation, operating conditions, as well as environmental factors and surrounding objects that may influence RF EMF propagation (e.g., building dimensions, nearby structures for outdoor installations, construction materials, floor layout).

3.6.3 Measurements at workplaces

Measurements at workplaces are intended to determine the actual exposure levels of workers in environments where private networks are operational. These should focus on two main types of workplaces:

1. **Workplaces and worker-accessible locations with the highest expected exposures (maximum peak).**

This includes not only typical working conditions but also temporary situations that may occur during installation, maintenance, non-standard procedures, or similar activities.

2. **Workplaces and worker-accessible locations where workers spend prolonged periods.**

Even if exposure levels are very low in such locations, it is still important to assess worker exposure due to the long duration of occupancy.

These measurements should cover both infrastructure (base stations) and user equipment (e.g., M2M and IoT devices). They may be conducted separately for each source or as an aggregated total from all sources present at the measurement location. Measurements can be performed as:

- **Selective measurements** with extrapolation to determine worst-case exposure,
- **Measurements under full load**, or
- **Measurements of actual values** under normal working conditions.

In all cases, it must be clearly documented under which conditions the measurements were performed.

When performing measurements at a workplace, it is also necessary to assess the **time variability of exposure**. Therefore, additional measurements should be conducted either:

- **As time-controlled measurements** over at least 6 minutes, during which EMF values are recorded every few seconds. This method allows the calculation of different averaging periods and supports further analysis of the appropriate averaging time for 5G exposure estimation (preferred method), or
- **As a single 6-minute average measurement.** The drawback of this approach is that it provides only one averaged value, without information about exposure variability or the possibility of further analysis.

For each workplace, all relevant factors must be documented, including exposure duration, total daily time spent at the workplace, and any other relevant conditions.

3.6.4 Uncertainty budget

RF EMF measurements were performed using a Narda SRM-3006 spectrum analyzer with suitable antennas. For FR1 and Wi-Fi 6 applications, a Narda 3502 three-axis antenna was used, while for FR2 applications, a Narda LNB 1 horn antenna was employed. The expanded measurement uncertainty of the equipment was ± 3.5 dB (see Table 4) for the FR1 frequency band, ± 3.1 dB for FR2 frequency band and ± 3.8 dB for the 5 GHz frequency band.

Table 4: Measurement uncertainty of the equipment used for FR1 measurements.

Source of Uncertainty	Uncertainty [dB]	Distribution	Divider	c_i	u [dB]	u^2
spectrum analyzer						
error of frequency steep sample (est.)	0.20	square	1.73	1	0.12	0.01
attenuator error 0–50 dB (est.)	0.20	square	1.73	1	0.12	0.01
temperature drift (est.)	0.50	square	1.73	1	0.29	0.08
modulation (est.)	0.20	square	1.73	1	0.12	0.01
antenna						
interpolation of antenna factor (est.)	0.10	square	1.73	1	0.06	0.00
anisotropy (cal.)	2.43	normal	2	1	1.22	1.49
spectrum analyzer + antenna						
calibration uncertainty (cal.)	1.23	normal	2	1	0.62	0.38
frequency response (cal.)	0.63	normal	2	1	0.32	0.10
nonlinearity (cal.)	0.18	normal	2	1	0.09	0.01
mismatch SA—antenna	0.25	U	1.41	1	0.18	0.03
external data and method						
uncertainty of external technical data (est.)	0.27	square	1.73	1	0.16	0.03
influence of human body, positioning of antenna... (est.)	1.00	square	1	1	1.00	1.00
Combined standard uncertainty u [dB]					1.77	3.15
Expanded measurement uncertainty U [dB]		normal	2		3.54	

4 Measured scenarios and exposures

Several scenarios of exposure have been measured, including production facilities, logistics, offices and research. There were several different types of installations: private standalone (SA) and non-standalone (NSA) 5G networks at 3.5 GHz and 26 GHz, public 5G networks with private slicing as well as a WiFi-6 local network at 5 GHz.

4.1 Scenario 1: Logistic sector: Port of Koper, private 5G FR1

In the Port of Koper, two 5G deployment scenarios were assessed. The first scenario involved the installation of a private standalone (SA) 5G network operating at 3.5 GHz. Measurements were carried out primarily at a test site outside the Port, where accessibility and environmental control were easier to ensure, but additional measurements were also performed on a test installation located within the Port itself.

4.1.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 5.

Table 5: Detailed information regarding the installation.

Location description	
type of location	logistics - Port
type of installation	private test site
Antenna parameters	
antenna model	Alpha Wireless AW 3232
antenna type	directional
antenna gain [dBi]	15
location of antenna	on pole
antenna height (middle) [m]	1.9
antenna size [m]	0.75
downtilt [°]	0
envelope of radiation pattern in use	only one radiation pattern, no beamforming
Cell parameters	
type	5G
frequency band	3.5 GHz
central frequency [MHz]	3410
channel number (center)	627333
bandwidth [MHz]	20
MIMO configuration	2×2
max output power [W]	2×2
max output power [dBm]	2×33 dBm
duty cycle	0.6
power of pilot signal [dBm]	2×6
frequency of the pilot [MHz]	3410.4
pilot channel number	627360
PCI	0
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	measurements under load with real live monitoring of output power



Figure 2: Source during measurements for test setup.

4.1.2 Results of line measurements

Line measurements were carried out at the height of 1.5 m.

Table 6: Results for line measurements. Main beam measurements were done in the direction of the main beam of the antenna, whereas directions 45° from main beam and 90° from main beam are directions 45 and 90 from the main beam of the antenna.

distance [m]	$E_{\text{main beam}}$ [V/m]	$E_{45^\circ \text{ from main beam}}$ [V/m]	$E_{90^\circ \text{ from main beam}}$ [V/m]
0.2	75.69	63.30	37.62
0.5	50.64	58.30	26.09
1	34.28	36.55	19.78
2	13.95	10.61	11.15
3	8.49	7.67	7.02
4	4.10		
5	4.19	4.07	
6	3.76		
7	3.61		
8	2.70		
9	2.14		
10	2.47		
20	1.36	63.30	37.62

4.1.3 Results of raster measurements

Raster measurements were carried out at a height of 1.5 m above ground. Due to surrounding limitations measurements were made only up to a distance of 20 m and 10 m right of the antenna.

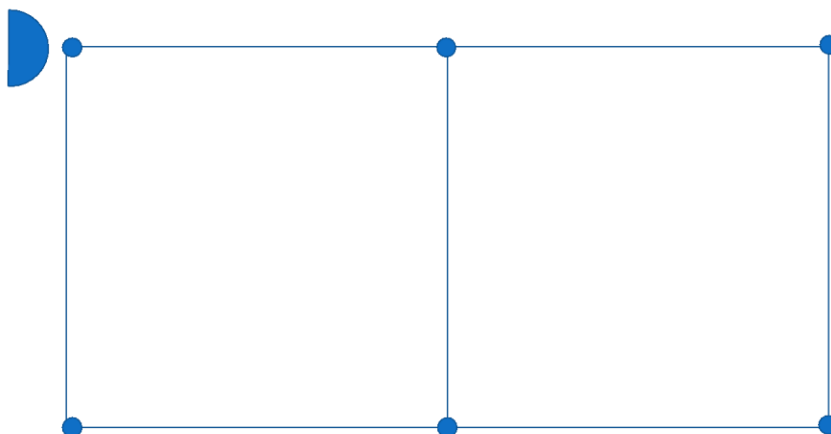


Figure 3: Results for raster measurements at a height of 1.5 m.

Table 7: Results of raster measurements at a height of 1.5 m.

type of result	E [V/m]
95th percentile	21.97
median value	2.28
standard deviation	16.02
variance	89.38

4.1.4 Time variability

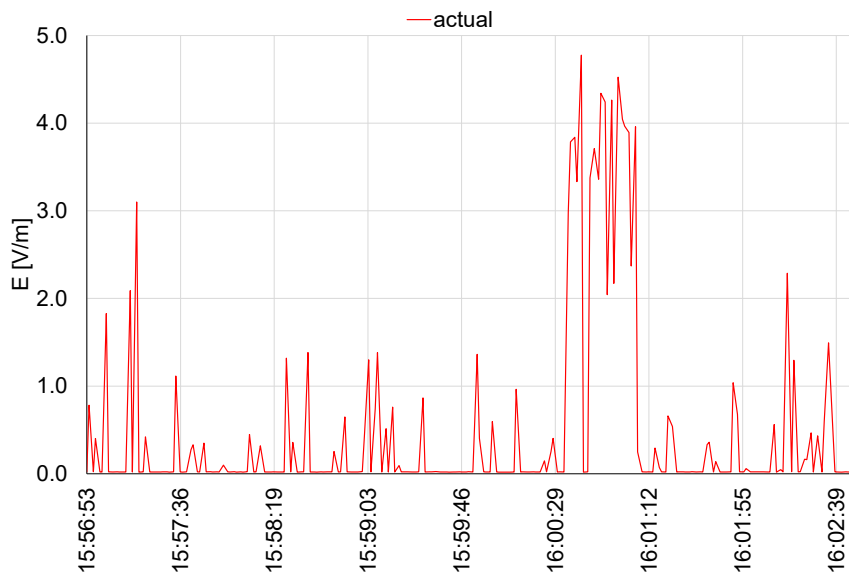


Figure 4: Temporal measurements of the whole 5G bandwidth 5 m in front of the antenna.

To capture time variability of the signals, measurements of the whole 5G band in use were done for a duration of 6 minutes. Measurements were taken 5 m in front of the antenna. The base station was under normal working conditions operating at a power of 2×2 W. From the results, the 6-minute average value was calculated as a root of mean square.

Table 8: Results of raster measurements at the height of 1.5 m.

type of result	E [V/m]
maximum value	4.78
95th percentile	3.55
mean value	1.16
median value	0.02
standard deviation	2.02
variance	1.11

From Table 8 and Figure 4 it can be seen that due to low traffic the values are low, the mean value being only slightly above 1 V/m. When there was some traffic, the actual values were between 2.5 and 5 V/m.

4.2 Scenario 2: Logistic sector: Port of Koper, public slice 5G FR1

In the Port of Koper, the second scenario was based on a private slice within the existing public 3.5 GHz 5G network (Figure 5). This private slice relied exclusively on base stations located inside the Port of Koper, and all core infrastructure was also hosted within the Port area. Consequently, no information from the private slice left the premises of the Port of Koper.



Figure 5: Source under test.

4.2.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 9.

Table 9: Detailed information regarding the installation.

Location description	
type of location	logistics – Port
type of installation	public site with test private slice
Antenna parameters	
antenna model	Ericsson AIR 3227
antenna type	directional
antenna gain [dBi]	23.5
location of antenna	on pole
antenna height (middle) [m]	9.2
antenna size [m]	0.54
downtilt [°]	0
envelope of radiation pattern in use	beamforming
Cell parameters	
type	5G
frequency band	3.5 GHz
central frequency [MHz]	3470
channel number (center)	631333
bandwidth [MHz]	100
MIMO configuration	8×8
max output power [W]	100
max output power [dBm]	50
duty cycle	0.8
power of pilot signal [dBm]	/
frequency of the pilot [MHz]	3430.56
pilot channel number	628704
PCI	261
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	code selective measurements, band selective measurements under load

4.2.2 Results of line measurements

Line measurements were carried out at a height of 1.5 m. Due to high position of the antenna (9.2 m) the first measurement was done at a distance of 10 m. Measurements were performed under speed test conditions and electric field of the whole frequency band (100 MHz) was measured.

Table 10: Results for line measurements. Main beam measurements were done in the direction of the main beam of the antenna, whereas directions 45° from main beam and 90° from main beam are directions 45 and 90 from the main beam of the antenna.

Distance	<i>E</i> [V/m]
10	4.56
20	19.00
30	24.22
40	6.06
50	14.04
100	4,03

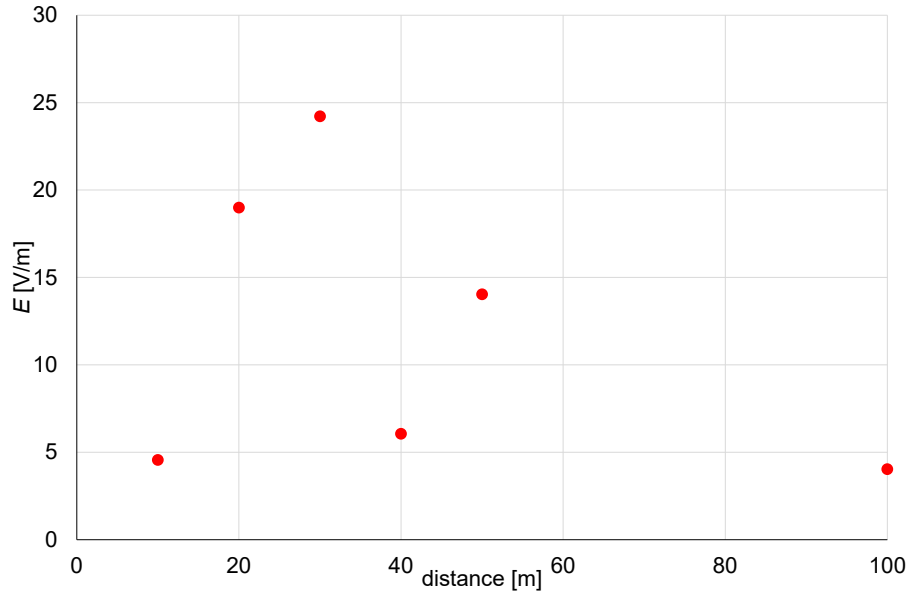


Figure 6: Results for line measurements. Measurements were done in the direction of the main beam of the antenna as band selective measurements under speed test.

4.2.3 Results of raster measurements

Raster measurements were done on a 10×10 m grid under speed test conditions to generate maximum values. Raster measurements were done up to a distance of 50 m.



Figure 7: Locations of raster measurements.

Table 11: Results of raster measurements at the height of 1.5 m.

measurement location	E [V/m]	measurement location	E [V/m]
1	2.06	7	1.40
2	3.56	8	6.19
3	13.30	9	17.55
4	24.22	10	12.17
5	6.06	11	10.01
6	13.62	12	14.86
95th percentile	20.82		
median value	11.14		
standard deviation	12.98		
Variance	47.09		

4.2.4 Time variability

To capture time variability of the signals, measurements of the pilot signal and the whole 5G band in use were done for the duration of one hour. Measurements were taken in the direction of the main beam at a distance of 50 m from the antenna and at a height of 1.5 m. From the results, the average values for different averaging durations were calculated. Average values were calculated as a root of mean square.

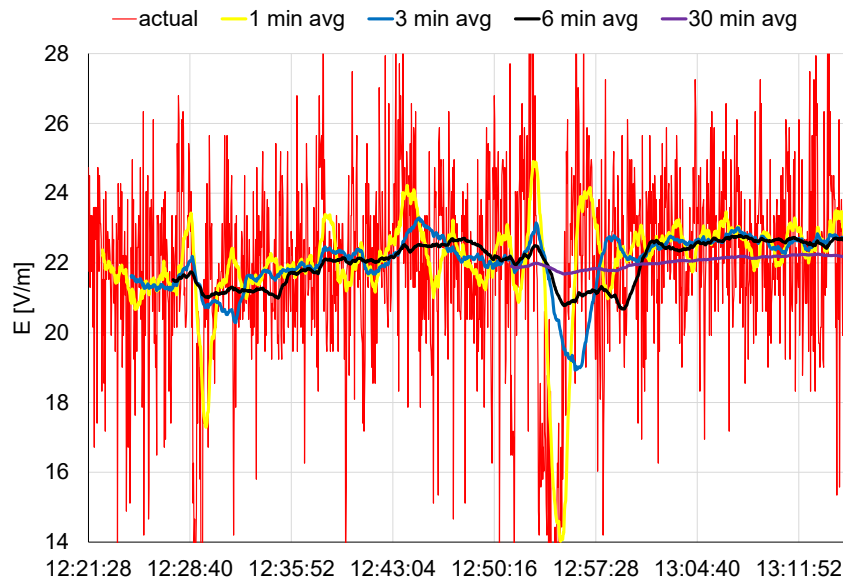


Figure 8: Temporal measurements of the pilot signal 50 m from the antenna in the direction of the main beam. The results are given for the extrapolated maximum value. Besides the actual value, also 1-, 3-, 6- and 30-minute average values are presented.

From the results shown in Figure 8, it can be observed that shorter averaging times provide a good approximation of the 6-minute average value. Over the entire measurement period, the maximum difference between the 1-minute and 6-minute averages was 33%, while for the 2-minute average it was 22%, and for the 3-minute average it was 10%.

However, this relationship does not hold for measurements of the entire 5G frequency band in use. Shorter averaging times differ significantly from the 6-minute average. Over the full measurement period, the maximum difference between the 1-minute and 6-minute averages was 87%, for the 2-minute average it was 52%, and for the 3-minute average it was 30%. These large differences are caused by the operating conditions of the network under test. Although the base station was operational, it was active only for a fraction of the time, so intermittent high values had a strong influence on the average.

4.2.5 Space variability

Detailed measurements to evaluate spatial averaging were performed at a single location in the direction of the antenna's main beam, at a distance of 50 m from the antenna.

Measurements followed the IEC 62232:2022 [3] spatial averaging scheme, with three heights (1.1 m, 1.5 m, and 1.7 m) and three lateral positions (center, 0.2 m to the left, and 0.2 m to the right), yielding a total of nine measurement points. Two additional vertical planes were included, positioned 0.2 m in front and 0.2 m behind the central plane, increasing the total number of measurements to 27.

From these results following average values were calculated:

- 3-point average value: central points at heights 1.1 m, 1.5 m and 1.7 m,
- 9-point average value: points in a central vertical plane at heights 1.1 m, 1.5 m and 1.7 m,
- 27-point average value: all 27 measurement points,
- 9-point average at 1.1 m: all 9 measurement points at 1.1 m,
- 9-point average at 1.5 m: all 9 measurement points at 1.5 m and
- 9-point average at 1.7 m: all 9 measurement points at 1.7 m.

From the results in Table 12, it can be observed that for the pilot signal all averaging schemes produced similar values. Measured pilot signal values ranged from 0.095 to 0.228 V/m with the averaged values ranged from 0.136 to 0.151 V/m. Variability of the extrapolated maximum values was greater, with measured values 20.80 and 48.99 V/m and averaged values ranging from 32.27 to 36.42 V/m. The differences between the various averaging methods were not significant.

Table 12: Results of space variability measurements.

measurement	x [m]	y [m]	h [m]	E_{pivot} [V/m]	K	E_{max} [V/m]
7_1	-0.2	-0.2	1.1	0.153	263.73	40.46
8_1	-0.2	0.0	1.1	0.151	263.66	39.68
9_1	-0.2	0.2	1.1	0.161	263.73	42.36
4_1	0.0	-0.2	1.1	0.116	260.46	30.21
5_1	0.0	0.0	1.1	0.160	260.40	41.53
6_1	0.0	0.2	1.1	0.154	260.46	40.11
1_1	0.2	-0.2	1.1	0.125	257.26	32.05
2_1	0.2	0.0	1.1	0.126	257.20	32.41
3_1	0.2	0.2	1.1	0.096	257.26	24.64
7_2	-0.2	-0.2	1.5	0.117	231.02	27.01
8_2	-0.2	0.0	1.5	0.145	230.96	33.51
9_2	-0.2	0.2	1.5	0.163	231.02	37.70
4_2	0.0	-0.2	1.5	0.121	229.10	27.63
5_2	0.0	0.0	1.5	0.145	229.04	33.10
6_2	0.0	0.2	1.5	0.136	229.10	31.18
1_2	0.2	-0.2	1.5	0.148	227.22	33.54
2_2	0.2	0.0	1.5	0.122	227.16	27.78
3_2	0.2	0.2	1.5	0.181	227.22	41.06
7_3	-0.2	-0.2	1.7	0.095	218.85	20.80
8_3	-0.2	0.0	1.7	0.135	218.79	29.60
9_3	-0.2	0.2	1.7	0.096	218.85	21.08
4_3	0.0	-0.2	1.7	0.132	217.08	28.74
5_3	0.0	0.0	1.7	0.136	217.03	29.45
6_3	0.0	0.2	1.7	0.113	217.08	24.53
1_3	0.2	-0.2	1.7	0.228	215.34	48.99
2_3	0.2	0.0	1.7	0.189	215.28	40.67
3_3	0.2	0.2	1.7	0.177	215.34	38.05
one point (5-2)	0.0	0.0	1.5	0.145		33.10
3-point average	0.0	0.0	1.5	0.147		35.06
9-point average	0.0	0.0	1.5	0.136		32.27
27-point average	0.0	0.0	1.5	0.145		33.98
9-point average 1.1 m	0.0	0.0	1.1	0.140		36.42
9-point average 1.5 m	0.0	0.0	1.5	0.143		32.81
9-point average 1.7 m	0.0	0.0	1.7	0.151		32.57

4.3 Scenario 3: Smart Industry 4.0: Warehouse, private 5G FR1

The objective of this section is to present a systematic approach for assessing workers' RF EMF exposure from a private standalone (SA) 5G network in a warehouse and production hall of a leading smart industry facility, using a case study.

In the warehouse, designed for the storage of materials and finished products, a private 5G network was installed. The building covers approximately 3,400 m² and is primarily constructed of concrete, with a metal roof at a height of 5.5 m. Inside, six rows of pallet racks are arranged with corridors between them, covering roughly 40% of the warehouse area.

The private SA 5G network operates in the mid-band 5G frequency spectrum (band n78), allocated the range 3700–3800 MHz for industrial use. For indoor coverage, Nokia AirScale indoor radioheads (ASiR-pRRHs, model AWHQB) serve as small cell access points with a maximum output power of 1 W. Each pRRH is connected via an ASiR hub with direct optical fiber to the baseband unit (BBU) and the core server in the central data center. The industrial private network under test comprises four pico-RRHs (pRRHs) distributed across the warehouse, mounted on roof beams at a height of approximately 5 m. The radiation pattern of the pRRHs is nearly isotropic.

4.3.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 13.

Table 13: Detailed information regarding the installation.

Location description	
type of location	logistics – warehouse
type of installation	private operational site
Antenna parameters	
antenna model	4 pico indoor remote radioheads Nokia AirScale SiR-pRRH AWHQB
antenna type	omnidirectional
antenna gain [dBi]	0
location of antenna	under ceiling
antenna height (middle) [m]	5
antenna size [m]	≈0.3
downtilt [°]	0
envelope of radiation pattern in use	only one radiation pattern, no beamforming
Cell parameters	
Type	5G
frequency band	3.5 GHz
central frequency [MHz]	3750
channel number (center)	650000
bandwidth [MHz]	100
MIMO configuration	4×4
max output power [W]	4×0.25
max output power [dBm]	4×24
duty cycle	0.6
power of pilot signal [dBm]	-11.15
frequency of the pilot [MHz]	3748
pilot channel number	649920
PCI	606
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	code selective measurements, band selective measurements

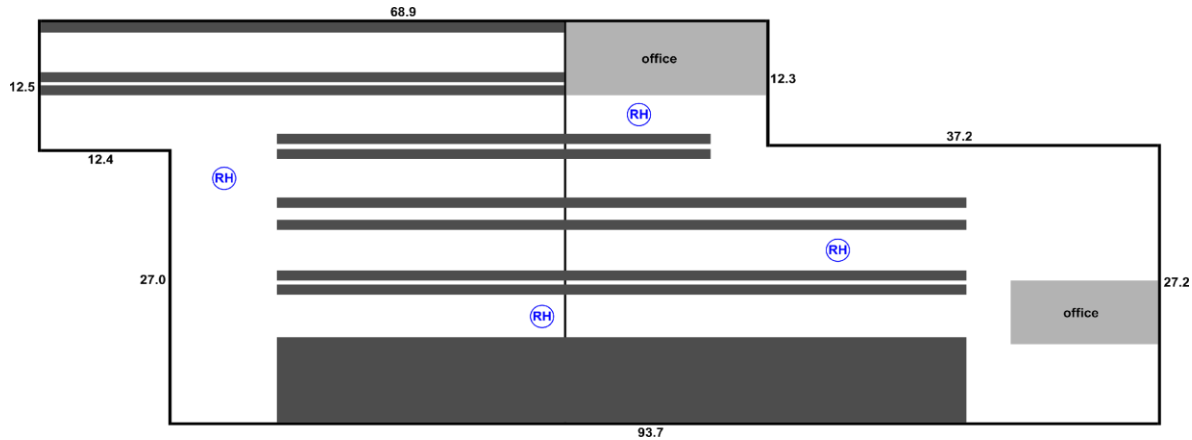


Figure 9: Geometry of the warehouse. Black blocks represent the walls, dark gray the rows of pallet racks and light gray the offices. Blue text RH represents locations of the pRRH-s.

4.3.2 Results of raster measurements

Due to limitations imposed by pallet racks, raster measurements were slightly modified. Instead of 10×10 m grid, measurements along the corridors were taken with a spacing of 10 m. During the measurements, the network was in normal working state, but there was no traffic. Therefore, code-selective measurements were performed to measure the electric field due to the pilot signal. The maximum electric field value was calculated by extrapolating code-selective results to maximum power.

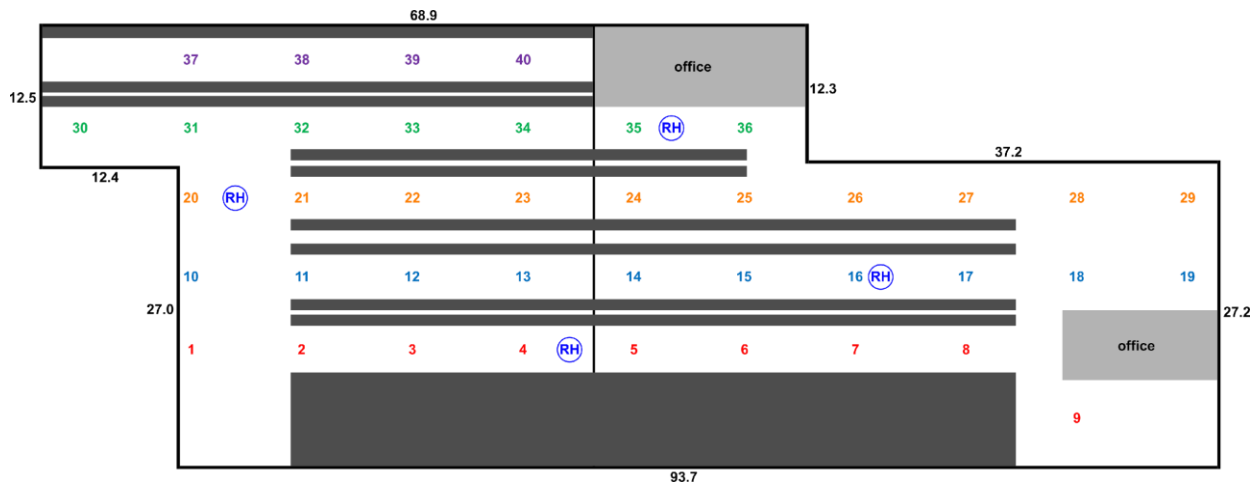


Figure 10: Locations of raster measurements.

Table 14: Results of raster measurements [6].

measurement location	E [V/m]	measurement location	E [V/m]	measurement location	E [V/m]
1	0.59	15	0.40	29	0.17
2	0.38	16	1.41	30	0.38
3	0.43	17	0.75	31	0.71
4	0.74	18	0.42	32	0.63
5	0.34	19	0.25	33	0.33
6	0.27	20	1.25	34	0.22
7	0.25	21	0.87	35	0.77
8	0.47	22	0.56	36	0.64
9	0.13	23	0.23	37	0.31
10	1.00	24	0.28	38	0.16
11	0.51	25	0.52	39	0.12
12	0.18	26	0.42	40	0.08
13	0.25	27	0.49		
14	0.18	28	0.18		
95th percentile	1.01				
median value	0.39				
standard deviation	0.64				
variance	0.09				

Results of measurements clearly show that the electric field strength values were low at all locations accessible to workers in the warehouse. The 95th percentile value was 1.01 V/m.

4.3.3 Time variability

To capture the time variability of the signals, measurements of both the pilot signal and the entire 5G frequency band in use were conducted over a period of more than 30 minutes. Measurements were taken at the side of the corridor, under the pRRH, near location 4 of the raster measurement grid. From the results, average values for different averaging durations were calculated using the root-mean-square method.

From the results in Figure 11, it can be observed that shorter averaging times provide a good approximation of the 6-minute average value. Over the full measurement period, the maximum difference between the 1-minute and 6-minute averages was 7%, while the differences for the 2-minute and 3-minute averages were 5% and 3%, respectively.

However, this does not hold for measurements of the entire 5G band in use. Shorter averaging times differ significantly from the 6-minute average. Across the measurement period, the maximum difference between the 1-minute and 6-minute averages was 102%, while the differences for the 2-minute and 3-minute averages were 53% and 30%, respectively. These large discrepancies are explained by the operating conditions of the network under test. Since the traffic volume was very limited, intermittent high values had a disproportionately strong influence on the averages.

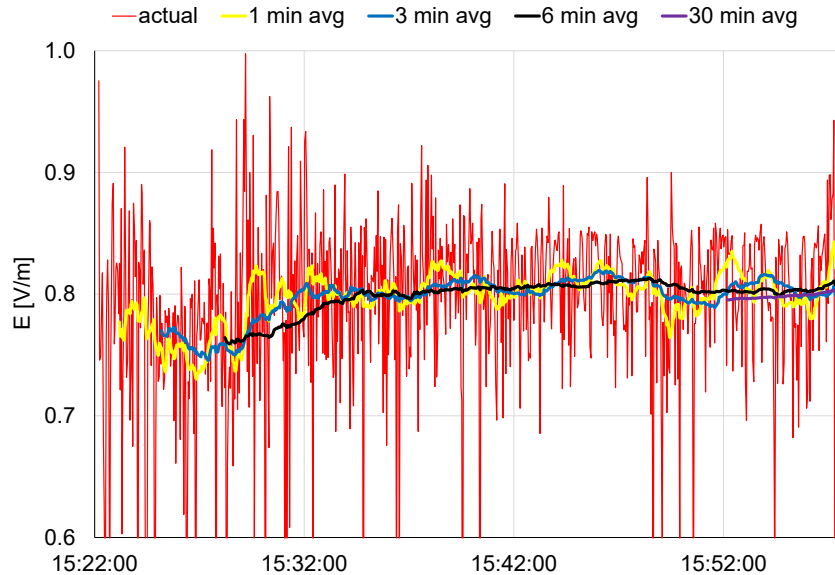


Figure 11: Temporal measurements of pilot signal under the pRRH. The results are given for the extrapolated maximum value. Besides the actual value, also 1-, 3- and 6-minute average values are presented.

4.4 Scenario 4: Smart Industry 4.0: Production Hall, private 5G FR1

At a production site for electronic device assembly and testing, a private 5G network was installed. The production hall covers approximately 2,800 m² and is primarily constructed of concrete, with a metal roof at a height of 6.9 m. Two sides of the hall contain two-level offices, with a balcony on the first floor at a height of 3.4 m. Most of the building is occupied by the main production hall, which includes several dedicated workstations for assembly and testing, organized into four rows separated by corridors. All equipment is relatively low, below 2.5 m. The effective coverage of the hall with equipment is less than 20%.

The private standalone (SA) 5G network operated in the mid-band 5G frequency spectrum (band n78), with the 3700–3800 MHz range allocated for industrial use. For indoor coverage, Nokia AirScale indoor radioheads (ASiR-pRRHs, model AWHQB) functioned as small cell access points, each with a maximum output power of 1 W. The pRRHs were deployed at all relevant locations within the production hall and were connected via ASiR hubs with direct optical fiber links to the baseband unit (BBU) and the core server in the central data center. The network under test comprised six pico-RRHs (pRRHs) distributed throughout the production hall. Four were mounted on roof beams at approximately 5.9 m, while two were installed on the balcony at around 3.1 m. The radiation pattern of the pRRHs was nearly isotropic.

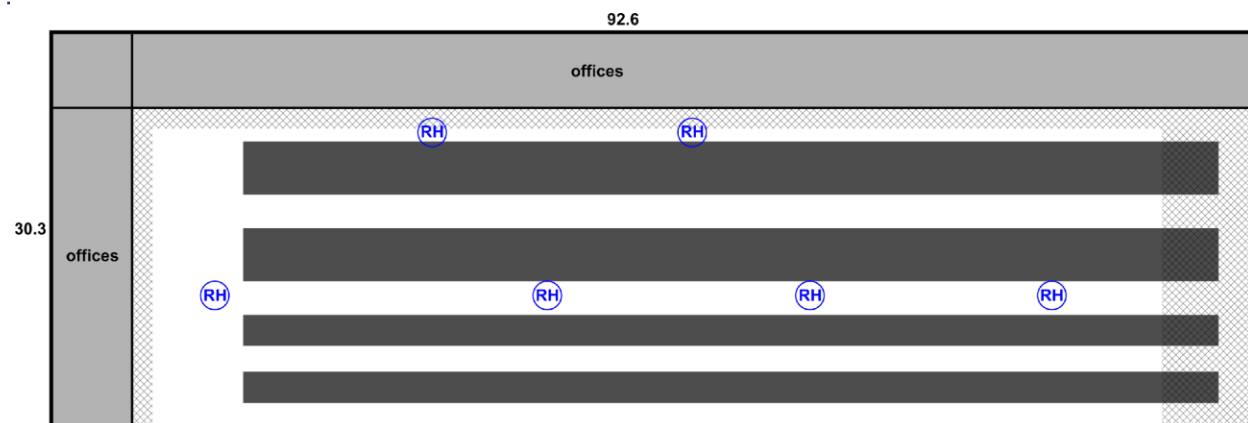


Figure 12: Geometry of the production hall. Black blocks represent the walls, dark gray the production areas with different equipment, light gray the offices and cross pattern the balcony. Blue text RH represents the locations of the pRRH-s.

4.4.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 15.

Table 15: Detailed information regarding the installation.

Location description	
type of location	production facility
type of installation	private operational site
Antenna parameters	
antenna model	5 pico indoor remote radioheads Nokia AirScale SiR-pRRH AWHQB
antenna type	Omnidirectional
antenna gain [dBi]	0
location of antenna	4 under ceiling and 2 under balcony
antenna height (middle) [m]	5.9 and 3.1
antenna size [m]	≈0.3
downtilt [°]	0
envelope of radiation pattern in use	only one radiation pattern, no beamforming
Cell parameters	
Type	5G
frequency band	3.5 GHz
central frequency [MHz]	3750
channel number (center)	650000
bandwidth [MHz]	100
MIMO configuration	4×4
max output power [W]	4×0.25
max output power [dBm]	4×24 dBm
duty cycle	0.6
power of pilot signal [dBm]	-11.15
frequency of the pilot [MHz]	3748
pilot channel number	649920
PCI	607
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	code selective measurements, band selective measurements

4.4.2 Results of raster measurements

Due to limitations imposed by the pallet racks, raster measurements were slightly modified. Instead of a 10 × 10 m grid, measurements along the corridors were taken at 10 m intervals. In addition to ground-level measurements, locations 1, 9, 10, 18, 19, and 27–36 were also measured from the balcony.

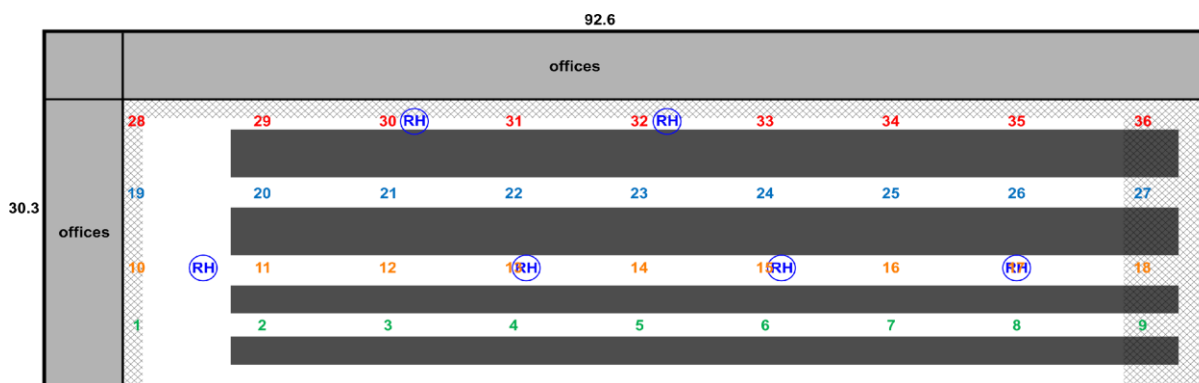


Figure 13: Locations of raster measurements.

During the measurements, the network operated in its normal mode, but no traffic was present. Therefore, code-selective measurements were performed to assess the electric field of the pilot signal. The maximum electric field value was estimated by extrapolating the code-selective results to the network's maximum output power.

Table 16: Results of raster measurements.

measurement location	E [V/m]	measurement location	E [V/m]
1	0.49	19	1.02
2	0.79	20	0.62
3	0.73	21	0.65
4	0.68	22	0.58
5	0.83	23	0.70
6	0.52	24	1.28
7	1.14	25	0.91
8	0.85	26	0.61
9	1.17	27	0.35
10	0.52	28	0.38
11	0.51	29	0.45
12	0.52	30	1.20
13	1.11	31	1.09
14	0.61	32	2.11
15	0.95	33	0.89
16	0.63	34	0.42
17	0.51	35	0.36
18	1.01	36	0.50
95th percentile		1.22	
median value		0.66	
standard deviation		0.88	
variance		0.12	

Table 17: Results of raster measurements on balcony.

measurement location	E [V/m]	measurement location	E [V/m]
1-balcony	1.33	30-balcony	0.64
9-balcony	1.09	31-balcony	0.57
10-balcony	0.80	32-balcony	1.13
18-balcony	1.45	33-balcony	0.88
19-balcony	0.41	34-balcony	0.52
27-balcony	1.00	35-balcony	0.58
28-balcony	0.30	36-balcony	0.34
29-balcony	0.39		
95th percentile	1.37		
median value	0.64		
standard deviation	0.80		
variance	0.14		

The exposure in the production hall was slightly higher compared to warehouse; for 36 measurements distributed through the whole production hall, the 95th percentile value was 1.22 V/m. The reason for the slightly higher values in the production hall was the number of objects in the environment. In the warehouse, there were several high pallet racks, mostly full of different items, whereas in the production hall the equipment was relatively low and covered only part of the production areas. Therefore, the attenuation of the EMF emitted by pRRHs was much lower in the production hall than in the warehouse. This led to higher values in the production hall.

4.4.3 Time variability

To capture time variability of the signals, measurements of the pilot signal and the whole 5G band in use were measured for a duration of more than 30 minutes. Measurements were taken under the pRRH mounted at the height of 3.1 m close to the location 32 of raster measurements. From the results, the average values for different averaging durations were calculated. Average values were calculated as a root of mean square.

From the results shown in Figure 14, it was observed that shorter averaging times provided a good approximation of the 6-minute average value. Over the full measurement period, the maximum difference between the 1-minute and 6-minute averages was 8%, while the differences for the 2-minute and 3-minute averages were 5% and 3%, respectively.

However, this did not hold for measurements of the entire 5G band in use. Shorter averaging times differed significantly from the 6-minute average. Across the measurement period, the maximum difference between the 1-minute and 6-minute averages was 95%, while the differences for the 2-minute and 3-minute averages were 80% and 78%, respectively. These large discrepancies were caused by the operating conditions of the network under test. Traffic was very limited, so intermittent high values had a disproportionately strong influence on the average.

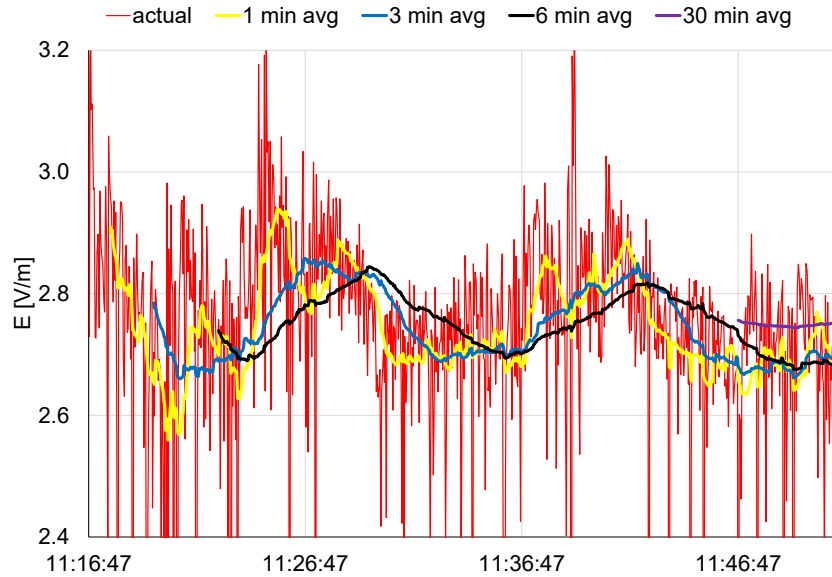


Figure 14: Temporal measurements of pilot signal under the pRRH mounted at the height of 3.1 m. The results are given for the extrapolated maximum value. Besides the actual value, also 1-, 3- and 6-minute average value are presented.

4.4.4 Detailed measurements under the radioheads



Figure 15: Extrapolated values of the measured electric field in the vicinity of a low-height pRRH in V/m. Measurements were taken at a height of 1.5 m in three directions at horizontal distances of 0.2, 0.5, 1, 2, 3, 4 and 5 m from the pRRH and directly below the pRRH at heights of 1, 1.5, 2, 2.5 and 2.8 m.

The maximum value in the production hall was measured at a location close to the lowest two pRRHs. In the warehouse, all four pRRHs were mounted at a height of about 5 m, whereas in the production hall four of them were mounted at a height of about 5.9 m and two at a height of 3.1 m. Due to the closer proximity of the pRRHs mounted at a height of 3.1 m, it was expected that the highest values would be measured there. It is not expected that pRRHs will be mounted significantly lower than the analyzed case; therefore, this situation represents the worst-case scenario that is expected to be found in private network installations. To further analyze the worst-case scenario, 22 additional detailed measurements were performed in the vicinity of one of the pRRHs mounted at a height of 3.1 m and 21 additional detailed measurements were performed under one pRRH mounted at 5.9 m.

Measurements were taken at a height of 1.5 m above the floor in two perpendicular directions intersecting directly below each pRRH. Measurement points were spaced 1 m apart, with additional points at 0.2 m and 0.5 m for the pRRH mounted at 3.1 m. Since this pRRH represented a worst-case scenario for potential worker RF EMF exposure due to its lower height, measurements were also performed at multiple heights along a vertical line below the antenna, at heights of 1 m, 1.5 m, 2 m, 2.5 m, and 2.8 m above the floor.

The results in Figure 16 and Figure 17 show that at the height of 1.5 the highest values are right below the pRRH, reaching values up to 3.1 V/m. At higher locations closer to the pRRH, the values increase to up to 8.9 V/m at the height of 2.8 m, which is 0.3 m below the pRRH.

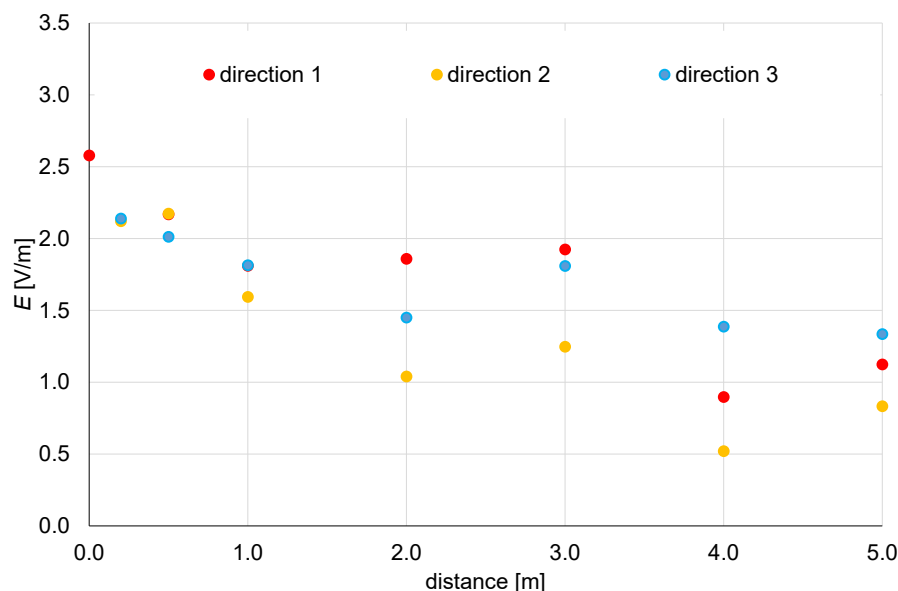


Figure 16: Results for detailed measurements under the pRRH mounted at the height of 3.1 m. Measurements were done at the height of 1.5 m. Results are presented for all three measured directions from the pRRH.

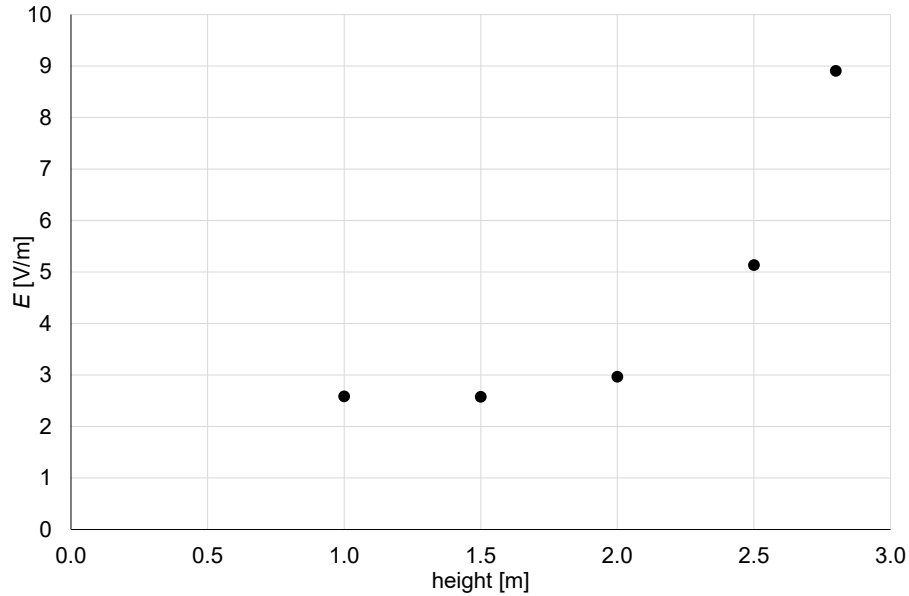


Figure 17: Results for detailed measurements under the pRRH mounted at the height of 3.1 m. Measurements were done at 5 different heights below the pRRH.



Figure 18: Results for detailed measurements under the pRRH mounted at the height of 5.9 m (located in the center). Measurements were done at the height of 1.5 m.

From the results in Figure 18 and Figure 19 for the measurements under pRRH mounted at the height of 5.9 m, we can see that the values are lower than those under the pRRH mounted on the balcony at the height of 3.1 m. The maximum value is 1.1 V/m, decreasing to 0.6 V/m or less at the distance of 5 m from the pRRH.

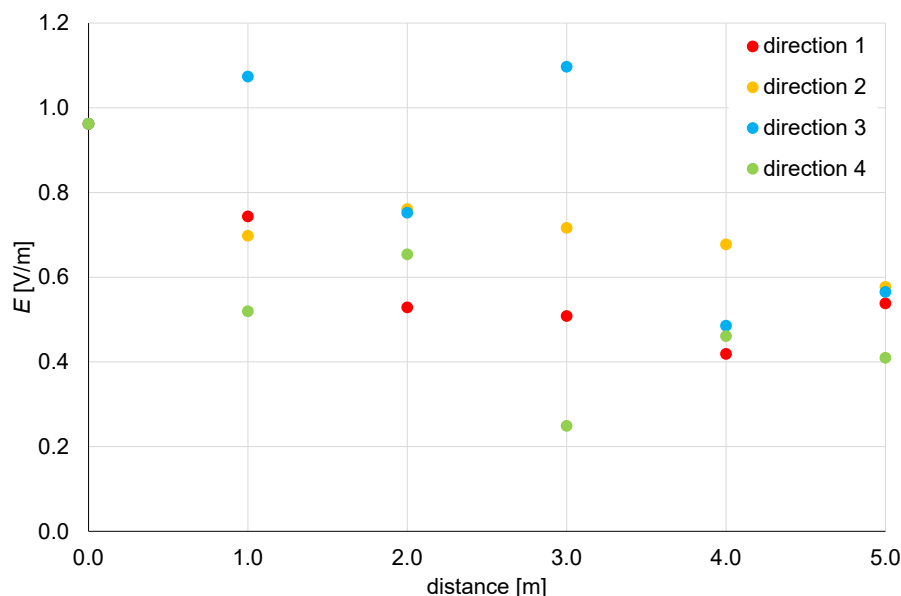


Figure 19: Results for detailed measurements under the pRRH mounted at the height of 5.9 m. Measurements were done at the height of 1.5 m. Results are presented for all four measured directions from the pRRH.

4.5 Scenario 5: Office, Test facility of wireless networks, private 5G FR1

A private 5G network was installed in an office hall covering approximately 400 m², primarily constructed of concrete, with a metal roof at a height of 7 m. One side of the hall featured metal doors approximately 6 m wide, extending the full height of the wall. The opposite side bordered additional offices, with metallic wall panels and several small windows. The hall contained no tall objects.

The private standalone (SA) 5G network operated in the 3420–3520 MHz frequency range. An Ericsson 6524 antenna, with dimensions of 0.2 × 0.2 m, was mounted on the wall at a height of 3 m. The power delivered to the antenna was 20 W.

4.5.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 18.

Table 18: Detailed information regarding the installation.

Location description	
type of location	test facility
type of installation	private operational site
Antenna parameters	
antenna model	Ericsson 6524
antenna type	directional
antenna gain [dBi]	12
location of antenna	on the wall
antenna height (middle) [m]	3
antenna size [m]	≈0.2×0.2

downtilt [°]	0
envelope of radiation pattern in use	only one radiation pattern, no beamforming
Cell parameters	
Type	5G
frequency band	3.5 GHz
central frequency [MHz]	3470
channel number (center)	631333
bandwidth [MHz]	100
MIMO configuration	4x4
max output power [W]	4x5, 20 total
max output power [dBm]	4x24
duty cycle	0.8
power of pilot signal [dBm]	/
frequency of the pilot [MHz]	3430.545
pilot channel number	628703
PCI	275
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	speed test, band selective measurements

Geometry of the situation is presented in Figure 22.

4.5.2 Results of line measurements

Line measurements were carried out at a height of 1.5 m and at the height of antenna (3 m). Line measurements were repeated twice: first under speed test conditions to capture maximum values, and second as code-selective measurements.

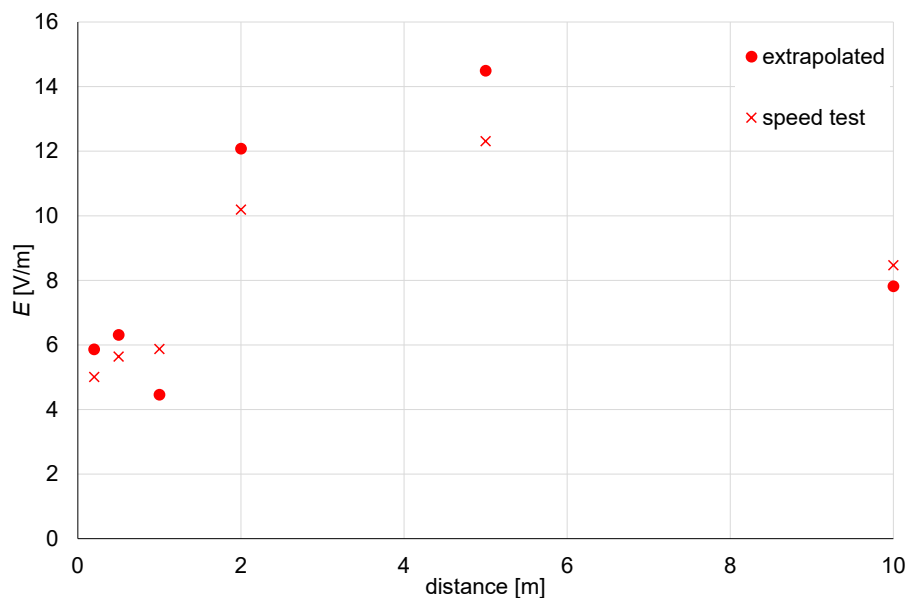


Figure 20: Results for line measurement at 1.5 m. Measurements were done in the direction of the main beam of the antenna. Circles represent extrapolated values based on measurements of pilot signal and x-marks broadband measurements under speed test.

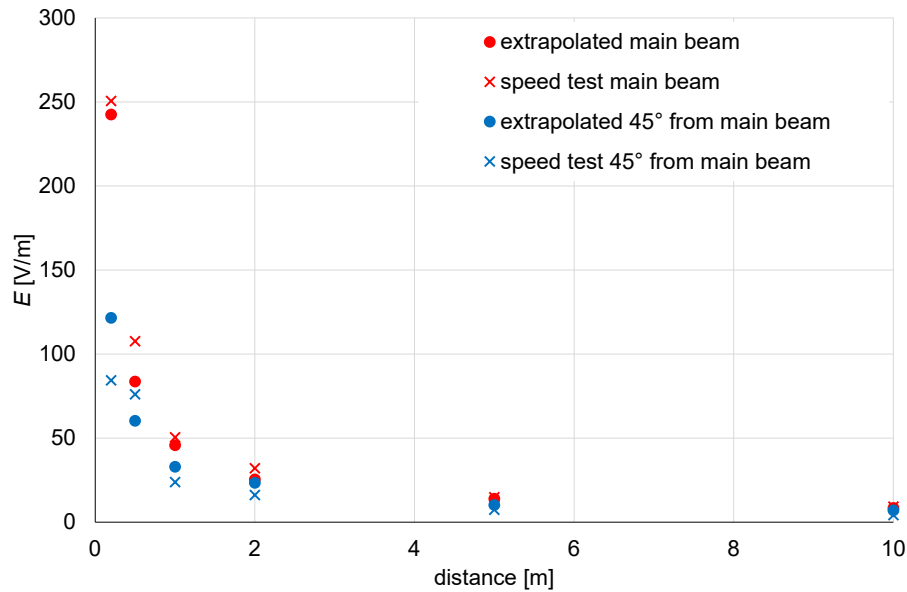


Figure 21: Results for line measurements at 3 m. Measurements in red were done in the direction of the main beam of the antenna whereas the blue ones were done in the direction of 45° from the main beam of the antenna. Circles represent extrapolated values based on measurements of the pilot signal and x-marks broadband measurements under speed test.

During the speed test measurements, the electric field across the entire frequency band used by the network was recorded while the network was actively transferring data to ensure maximum exposure values. For the code-selective measurements, the electric field of the pilot signal was measured. The maximum electric field value was then estimated by extrapolating the code-selective results to the network’s maximum output power.

Table 19: Results for line measurements. Measurements were done in the direction of the main beam of the antenna and in directions 45 from the main beam of the antenna.

distance [m]	main beam 1.5 m				main beam 3 m				45° from main beam 3 m			
	E_{pilot} [V/m]	K	E_{max} [V/m]	$E_{broadband}$ [V/m]	E_{pilot} [V/m]	K	E_{max} [V/m]	$E_{broadband}$ [V/m]	E_{pilot} [V/m]	K	E_{max} [V/m]	$E_{broadband}$ [V/m]
0.2	0.11	51.19	5.86	5.01	4.74	51.19	242.56	250.60	2.37	51.19	121.53	84.38
0.5	0.12	51.19	6.31	5.64	1.63	51.19	83.65	107.70	1.18	51.19	60.36	76.04
1	0.09	51.19	4.46	5.87	0.89	51.19	45.79	50.47	0.64	51.19	32.93	23.85
2	0.24	51.19	12.08	10.19	0.50	51.19	25.47	32.04	0.46	51.19	23.38	16.13
5	0.28	51.19	14.49	12.31	0.27	51.19	13.90	14.82	0.20	51.19	10.20	7.43
10	0.15	51.19	7.82	8.47	0.17	51.19	8.49	9.23	0.14	51.19	7.01	4.17

4.5.3 Results of raster measurements

Due to the small size of the facility, raster measurements were conducted on a 5 × 5 m grid instead of a 10 × 10 m grid. Raster measurements were repeated twice: first under speed test conditions to capture maximum values, and second as code-selective measurements. During the speed test, the electric field across the entire frequency band used by the network was recorded while the network was actively transmitting to ensure maximum exposure values. For the code-selective measurements, the electric field of the pilot signal was measured. The maximum

electric field value was then estimated by extrapolating the code-selective results to the network's maximum output power.

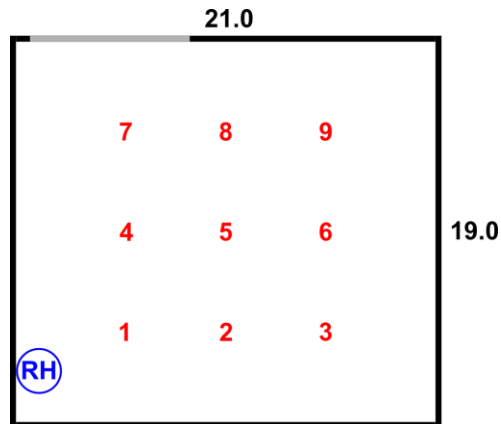


Figure 22: Locations of raster measurements.

Table 20: Results of raster measurements.

measurement location	E_{pilot} [V/m]	K	E_{max} [V/m]	$E_{broadband}$ [V/m]
1	0.23	51.19	11.63	9.38
2	0.18	51.19	9.24	7.30
3	0.07	51.19	3.72	7.84
4	0.15	51.19	7.68	4.64
5	0.10	51.19	5.05	7.28
6	0.16	51.19	8.31	6.71
7	0.06	51.19	3.07	3.22
8	0.09	51.19	4.78	4.72
9	0.10	51.19	4.98	4.88
95th percentile			10.74	8.79
median value			5.05	6.71
standard deviation			6.46	4.97
variance			8.17	3.83

4.5.4 Time variability

To capture time variability of the signals, measurements of the whole 5G band in use were conducted for the duration of 2 minutes. Measurements were taken in the main beam at the distance of 10 m and at the height of 1.5 m. During the measurements, the speed test was repeated three times. Due to the short measurement duration only one minute averaging was calculated. Average values were calculated as a root of mean square.

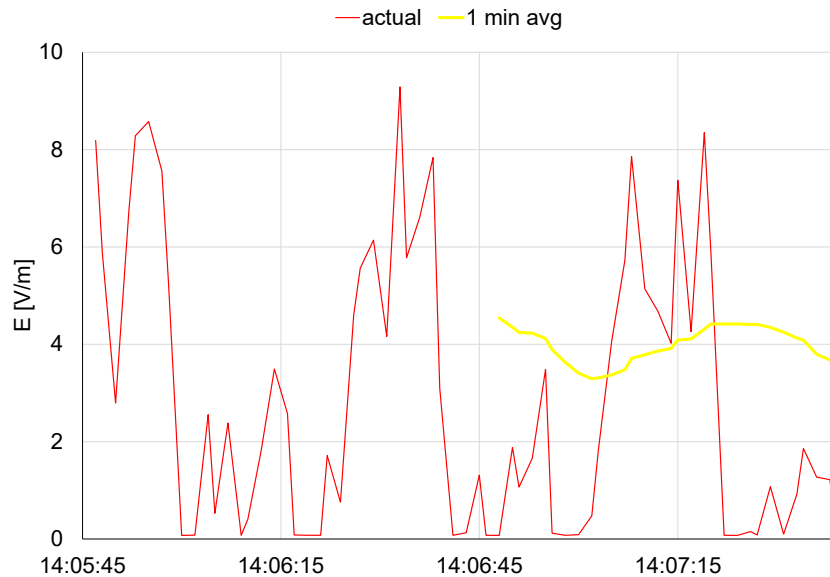


Figure 23: Temporal measurements of whole 5G band in the direction of the main beam at the distance of 10 m and at the height of 1.5 m. Beside the actual value (red), also the 1-minute average value is presented (yellow).

From the results shown in Figure 23, significant differences were observed in the measured values between periods of active speed testing and the intervals in between. During the measurements, no other users were connected except for a modem used to conduct the speed test, which included separate periods for download and upload testing.

4.5.5 Space variability

Detailed measurements to evaluate spatial averaging were conducted at a single location in the direction of the antenna's main beam, at a distance of 10 m from the antenna. Measurements followed the IEC 62232:2022 [3] spatial averaging scheme, with three heights (1.1 m, 1.5 m, and 1.7 m) and three lateral positions (center, 0.2 m to the left, and 0.2 m to the right), yielding a total of nine measurement points. Two additional vertical planes were added, positioned 0.2 m in front of and 0.2 m behind the central plane, increasing the total number of measurements to 27.

From these results, the following average values were calculated:

- 3-point average value: central points at heights 1.1 m, 1.5 m and 1.7 m,
- 9-point average value: points in a central vertical plane at heights 1.1 m, 1.5 m and 1.7 m,
- 27-point average value: all 27 measurement points,
- 9-point average at 1.1 m: all 9 measurement points at 1.1 m,
- 9-point average at 1.5 m: all 9 measurement points at 1.5 m and
- 9-point average at 1.7 m: all 9 measurement points at 1.7 m.

From the results in Table 21, it can be observed that the measurement at the central point (measurement 2-2-2) at a height of 1.5 m produced the lowest value of all measurements. This

is not a common situation, as the variability of values within a given volume typically varies from location to location. The differences between the averaging methods were not significant.

Table 21: Results of space variability measurements.

measurement	x [m]	y [m]	h [m]	E_{pilot} [V/m]	K	E_{max} [V/m]	$E_{broadband}$ [V/m]
1-1-1	-0.2	-0.2	1.1	0.28	51.19	14.52	
1-1-2	-0.2	0.0	1.1	0.18	51.19	9.40	
1-1-3	-0.2	0.2	1.1	0.19	51.19	9.55	
1-2-1	0.0	-0.2	1.1	0.23	51.19	11.71	
1-2-2	0.0	0.0	1.1	0.30	51.19	15.50	
1-2-3	0.0	0.2	1.1	0.19	51.19	9.81	
1-3-1	0.2	-0.2	1.1	0.19	51.19	9.81	
1-3-2	0.2	0.0	1.1	0.21	51.19	10.71	
1-3-3	0.2	0.2	1.1	0.21	51.19	10.74	
2-1-1	-0.2	-0.2	1.5	0.23	51.19	11.82	9.63
2-1-2	-0.2	0.0	1.5	0.22	51.19	11.30	9.96
2-1-3	-0.2	0.2	1.5	0.27	51.19	13.66	8.46
2-2-1	0.0	-0.2	1.5	0.20	51.19	10.16	7.68
2-2-2	0.0	0.0	1.5	0.18	51.19	9.35	8.24
2-2-3	0.0	0.2	1.5	0.20	51.19	10.19	7.94
2-3-1	0.2	-0.2	1.5	0.17	51.19	8.43	8.73
2-3-2	0.2	0.0	1.5	0.16	51.19	7.97	7.13
2-3-3	0.2	0.2	1.5	0.18	51.19	9.39	8.67
3-1-1	-0.2	-0.2	1.7	0.25	51.19	12.96	
3-1-2	-0.2	0.0	1.7	0.24	51.19	12.11	
3-1-3	-0.2	0.2	1.7	0.21	51.19	10.95	
3-2-1	0.0	-0.2	1.7	0.21	51.19	10.98	
3-2-2	0.0	0.0	1.7	0.25	51.19	12.54	
3-2-3	0.0	0.2	1.7	0.31	51.19	16.05	
3-3-1	0.2	-0.2	1.7	0.17	51.19	8.70	
3-3-2	0.2	0.0	1.7	0.18	51.19	9.25	
3-3-3	0.2	0.2	1.7	0.14	51.19	7.34	
one point (2-2-2)	0.0	0.0	1.5	0.18	51.19	9.35	8.24
3-point average	0.0	0.0	1.5			12.71	
9-point average	0.0	0.0	1.5			12.03	
27-point average	0.0	0.0	1.5			11.13	
9-point average 1.1 m	0.0	0.0	1.1			11.50	
9-point average 1.5 m	0.0	0.0	1.5			10.39	8.54
9-point average 1.7 m	0.0	0.0	1.7			11.47	

4.6 Scenario 6: Office, Production site, private 5G FR1

A private 5G network was installed in an office building. The network covered a single office and, to some extent, the surrounding corridors. The building's outer walls were made of concrete with numerous windows; however, the office itself was located internally, with no external walls, and was surrounded by corridors, other offices, and halls. Internal walls were mostly glass, and the ceiling height was 3.2 m. The office was mostly empty.

The private standalone (SA) 5G network operated in the 3400–3500 MHz frequency range. A Huawei PRRU 5961 pico remote radio unit was mounted on the ceiling, with an antenna size of approximately 0.2 × 0.2 m. The power delivered to the antenna was 0.63 W.

4.6.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 22.

Table 22: Detailed information regarding the installation.

Location description	
type of location	office
type of installation	private operational site
Antenna parameters	
antenna model	Huawei PRRU 5961
antenna type	omnidirectional
antenna gain [dBi]	unknown
location of antenna	on the ceiling
antenna height (middle) [m]	3.08
antenna size [m]	≈0.2×0.2
downtilt [°]	0
envelope of radiation pattern in use	only one radiation pattern, no beamforming
Cell parameters	
Type	5G
frequency band	3.5 GHz
central frequency [MHz]	3449.99
channel number (center)	629999
bandwidth [MHz]	100
MIMO configuration	4×4
max output power [W]	4×0.158
max output power [dBm]	4×12
duty cycle	0.8
power of pilot signal [dBm]	/
frequency of the pilot [MHz]	3449.28
pilot channel number	629952
PCI	341
sub carrier spacing (SCS) [kHz]	30
Measurement conditions	
type of measurements	speed test, band selective measurements

4.6.2 Results of line measurements

Line measurements were performed at a height of 1.5 m in three directions from the PRRH: at antenna height (3 m), directed 45° downward, and in the vertical direction.

Table 23: Results for line measurements at the height of 1.5 m.

distance [m]	E_{pilot} [V/m]	K	E_{max} [V/m]
0.2	0.022	51.19	1.12
0.5	0.091	51.19	4.64
1	0.017	51.19	0.85
2	0.026	51.19	1.31
5	0.019	51.19	0.97
10	0.009	51.19	0.48
95th percentile			4.07
median value			1.05
standard deviation			2.90
variance			2.36

The measurements were carried out as code-selective measurements, meaning that the electric field of the pilot signal was recorded. The maximum electric field value was then calculated by extrapolating the code-selective results to the maximum power.

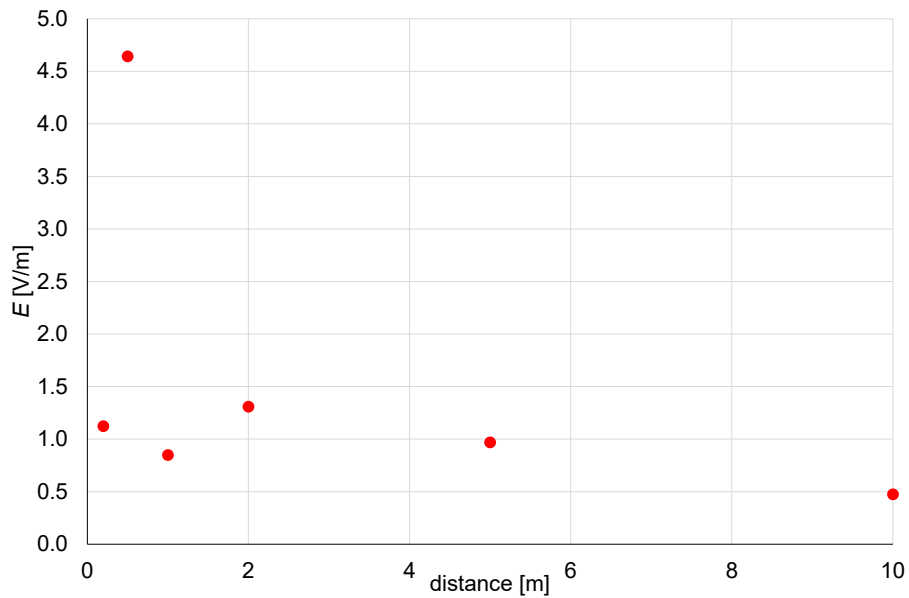


Figure 24: Results for line measurement at 1.5 m. Circles represent extrapolated values based on measurements of the pilot signal.

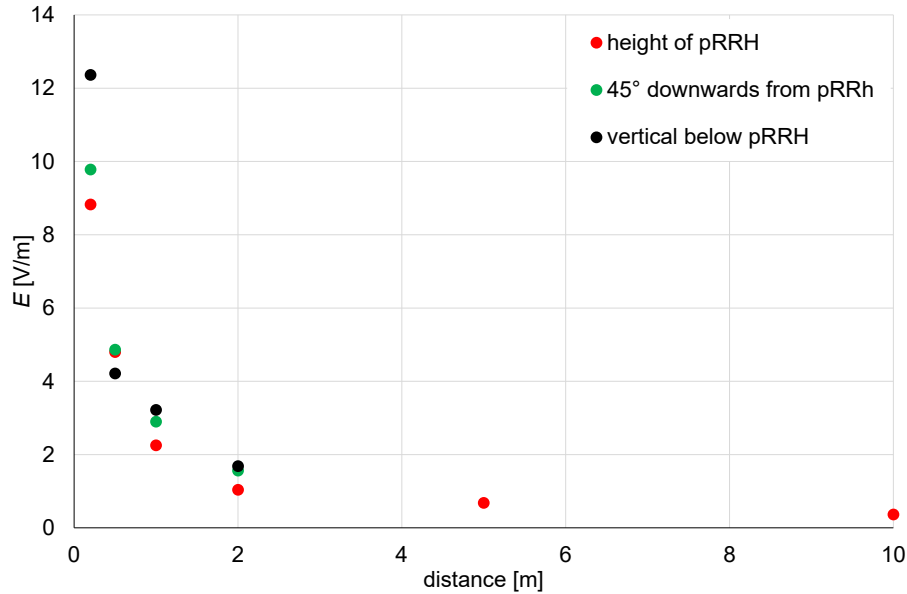


Figure 25: Results for line measurement in three directions form the PRRH. Circles represents extrapolated values based on measurements of the pilot signal. Measurements in red were done at the height of antenna (3 m), green in the direction of 45° downwards and black in vertical direction beneath the PRRH.

Table 24: Results for line measurements in three directions from the PRRH: at the height of antenna (3 m), directed 45° downwards and in vertical direction.

distance [m]	main beam 1.5 m			main beam 3 m			45° from main beam 3 m		
	E_{pilot} [V/m]	K	E_{max} [V/m]	E_{pilot} [V/m]	K	E_{max} [V/m]	E_{pilot} [V/m]	K	E_{max} [V/m]
0.2	0.172	51.19	8.83	0.191	51.19	9.78	0.242	51.19	18.11
0.5	0.094	51.19	4.80	0.095	51.19	4.86	0.082	51.19	6.99
1	0.044	51.19	2.25	0.057	51.19	2.90	0.063	51.19	4.24
2	0.020	51.19	1.04	0.031	51.19	1.56	0.033	51.19	2.13
5	0.013	51.19	0.68						
10	0.007	51.19	0.37						

4.6.3 Time variability

To capture time variability of the signals, measurements of the pilot signal and whole 5G band in use were conducted for a duration of more than one hour. Measurement points were 2 m below and 2 m away from the PRRH. From the results, the average values for different averaging durations were calculated. Average values were calculated as a root of mean square.

From the results shown in Figure 26, it was observed that shorter averaging times provided a good approximation of the 6-minute average value. Over the entire measurement period, the maximum difference between the 1-minute and 6-minute averages was 33%, while the differences for the 2-minute and 3-minute averages were 23% and 10%, respectively.

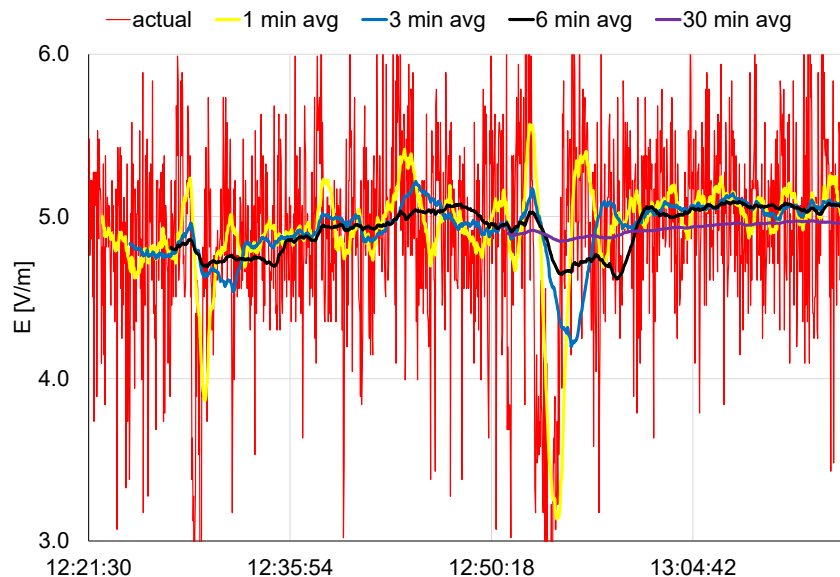


Figure 26: Temporal measurements of the pilot signal. The results are given for the extrapolated maximum value. Besides the actual value, also 1-, 3-, 6- and 30-minute average values are presented.

However, this did not hold for measurements of the entire 5G frequency band in use. Shorter averaging times differed significantly from the 6-minute average. Across the measurement period, the maximum difference between the 1-minute and 6-minute averages was 89%, while the differences for the 2-minute and 3-minute averages were 53% and 46%, respectively.

These large discrepancies were caused by the operating conditions of the network under test. Traffic was very limited, so intermittent high values had a disproportionate effect on the average.

4.7 Scenario 7: Research laboratory, private 5G FR2

In a research facility a private 5G test network is installed in an anechoic chamber. The size of the anechoic chamber is 12 m × 12 m.

The Private NSA 5G FR 2 network operates in the frequency range of 25.5-25.9 GHz. A Nokia AWEUC AirScale radio head is mounted on the movable pole at the height of 1.5 m, and the size of the antenna is about 0.2×0.2 m. The power delivered to the antenna was 1 W.

4.7.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 25.

Table 25: Detailed information regarding the installation.

Location description	
type of location	test installation in anechoic chamber
type of installation	private test site
Antenna parameters	
antenna model	Nokia AWEUC AirScale
antenna type	directional, vertical polarization
antenna gain [dBi]	27

location of antenna	on the pole
antenna height (middle) [m]	1.5
antenna size [m]	≈0.2×0.2
downtilt [°]	0
envelope of radiation pattern in use	two scenarios, one directional high gain with beamforming, one wide with no beamforming
Cell parameters	
Type	5G
frequency band	26 GHz
central frequency [MHz]	25700
channel number (center)	2040832
bandwidth [MHz]	400 (4 × 100)
MIMO configuration	2×2
max output power [W]	1
max output power [dBm]	30
duty cycle	0.8
power of pilot signal [dBm]	/
frequency of the pilot [MHz]	25563.36
pilot channel number	2038555
PCI	/
sub carrier spacing (SCS) [kHz]	240
Measurement conditions	
type of measurements	band selective measurements

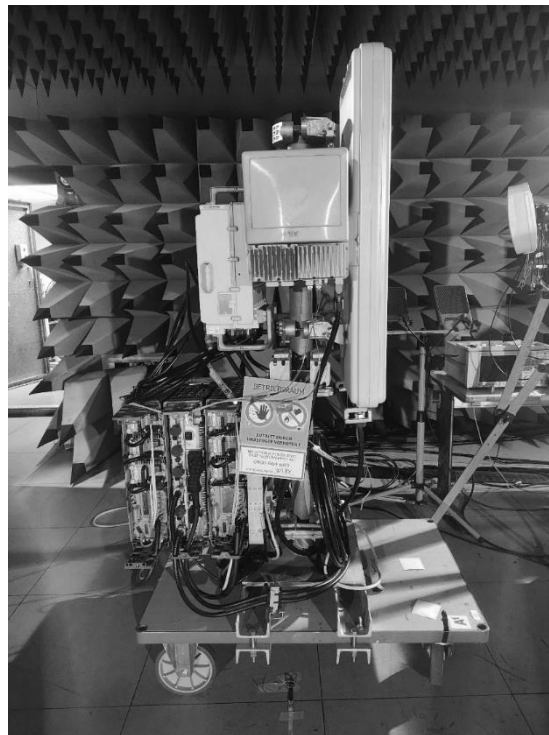


Figure 27: Location of the equipment under test.

4.7.2 Results of line measurements

Line measurements for the directional high gain with beamforming scenario were carried out at different distances from the antenna:

- in the direction of the main beam at the height of 0.5 m,
- in the direction of the main beam at the height of 1.5 m (height of antenna),
- in the direction of the main beam in a line 10° downwards from the antenna, as this is the direction of the highest gain of the scenario;
- 45° to the main beam in a line 10° downwards from the antenna;
- 90° to the main beam in a line 10° downwards from the antenna.

Line measurements were conducted under speed test conditions to capture maximum values. Additional user equipment (a mobile phone) was used to generate traffic, and the device was consistently positioned in the same direction as the measurement antenna. The speed test served as the source of traffic in the 5G network, producing approximately 1 Gbps during the measurement period. Band-selective measurements were performed to assess the entire frequency band used by the network, limited to the timeframe in which the speed test was active. The antenna was positioned in a corner of the anechoic chamber, approximately 2 m from both walls. Line measurements were done:

- horizontal orientation: direction of the main beam for vertical orientations:
 - at the height of 0.5 m;
 - at the height of 1.5 m;
 - in a line going 10° downwards from the antenna, which is vertical direction of the main beam;
- horizontal orientation 45° to the main beam for vertical orientation:
 - in a line going 10° downwards from the antenna, which is vertical direction of the main beam;
- horizontal orientation 90° to the main beam for vertical orientation:
 - in a line going 10° downwards from the antenna, which is vertical direction of the main beam.

Table 26: Results for line measurements in the direction of the main beam at the height of 0.5 m and 1.5 m. At the height of 1.5 m, measurements were repeated with a broadband detector.

distance [m]	<i>E</i> [V/m]		
	height 0.5 m	height 1.5 m	height 1.5 m broadband
1.0	2.19	59.65	62.0
2.0	3.34	23.00	29.9
3.0	6.42	16.24	19.3
4.0	9.02	14.04	15.9
5.0	9.74	11.69	11.9
6.0	10.78	9.78	10.2
7.0	7.28	8.75	8.4
8.0	4.55	7.54	6.1
9.0	6.88	6.84	6.0

Some measurements were repeated with broadband measurements, conducted with the Narda FieldMan instrument with probe EFD 5091 covering the whole frequency band from 100 MHz to 90 GHz.

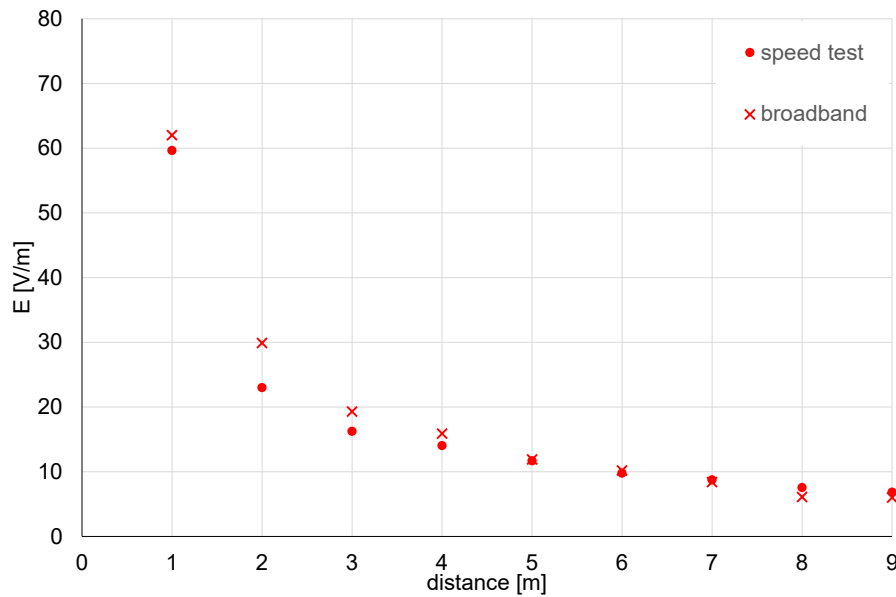


Figure 28: Results for line measurement at the height of 1.5 m in the direction of the main beam. Dots represent results of band selective measurements during speed test and x-marks results of additional measurements with the broadband detector covering the whole range from 100 MHz to 90 GHz.

Table 27: Results for line measurements in a line 10° downwards from the antenna which is vertical direction of the main beam. For the horizontal orientation of the main beam, measurements were repeated with a broadband detector.

distance [m]	height [m]	E [V/m]			
		main beam	main beam broadband	45° from main beam	90° from main beam
1.0	1.32	23.61	25.50	9.33	1.45
2.0	1.15	11.27	19.70	10.26	0.98
3.0	0.97	7.87	11.90	12.37	0.91
4.0	0.80	5.75	11.47	9.33	1.10
5.0	0.62	11.08	11.33	7.73	0.62
6.0	0.44	9.39	10.50	6.77	0.98
7.0	0.27	7.05	7.34	7.61	0.67
8.0	0.09	9.22	4.43	5.83	0.76

4.7.3 Time variability

To capture the time variability of the signals, measurements of the entire 5G frequency band in use were conducted over a period of approximately 10 minutes. Measurements were taken in

the main beam at a distance of 3 m and a height of 1 m. From the results, average values for different averaging durations were calculated, using the root-mean-square method.

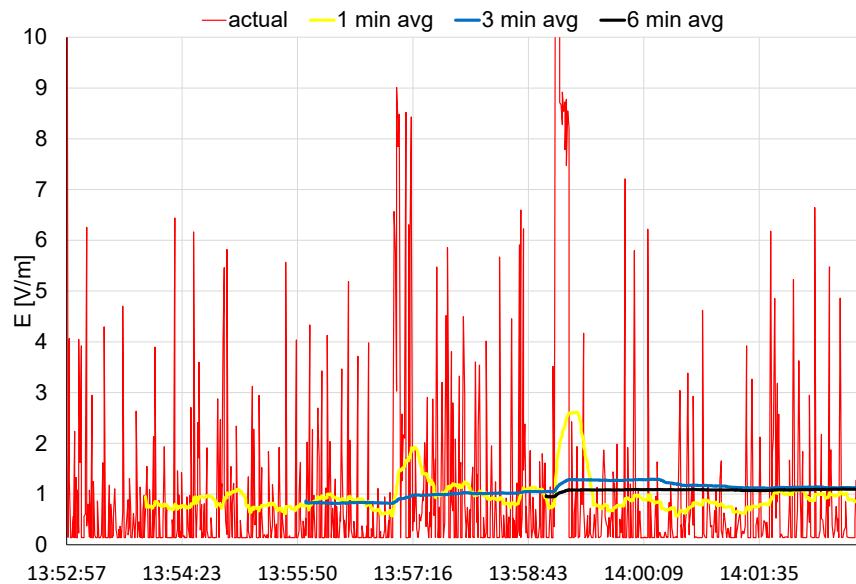


Figure 29: Temporal measurements of the whole 5G bandwidth. Besides the actual value, also 1-, 3- and 6-minute average values are presented.

From Figure 29 it can be seen that similar to other scenarios, shorter averaging times do differ from the 6-minute average value significantly. For the whole duration of measurements, the highest difference between the 1- and 6-minute average was 48%, between the 2- and 6-minute average was 34% and between 3- and 6-minute average was 19%. The reason for such big differences is the operating conditions of the network under test. The amount of traffic was very limited and therefore some intermittent high values had great influence on the average value.

4.7.4 Space variability

Detailed measurements to evaluate spatial averaging were conducted at a single location in the direction of the main beam, at a distance of 3 m from the antenna. Measurements followed the IEC 62232:2022 [3] spatial averaging scheme, with three heights (1.1 m, 1.5 m, and 1.7 m) and three lateral positions (center, 0.2 m to the left, and 0.2 m to the right), resulting in a total of nine measurement points. Two additional vertical planes were added, positioned 0.2 m in front of and 0.2 m behind the central plane, increasing the total number of measurements to 27.

From these measurements, the following average values were calculated:

- 3-point average value: central points at heights 1.1 m, 1.5 m and 1.7 m,
- 9-point average value: points in a central vertical plane at heights 1.1 m, 1.5 m and 1.7 m,
- 27-point average value: all 27 measurement points,
- 9-point average at 1.1 m: all 9 measurement points at 1.1 m,
- 9-point average at 1.5 m: all 9 measurement points at 1.5 m and
- 9-point average at 1.7 m: all 9 measurement points at 1.7 m.

From the results in Table 28, it was observed that the measurement at the central point (measurement 2-2-2) at a height of 1.5 m produced the highest value of all measurements. The differences between averaging methods were significant, with height being the most influential factor. This was expected due to the short distance between the measurement location and the antenna, as well as the high directivity of the antenna. A vertical displacement of only 0.2 m from the central point moved the measurement location out of the main beam, resulting in substantially lower values.

Table 28: Results of space variability measurements.

measurement	x [m]	y [m]	h [m]	$E_{broadband}$ [V/m]
1-1-1	-0.2	-0.2	1.1	12.85
1-1-2	-0.2	0.0	1.1	15.19
1-1-3	-0.2	0.2	1.1	9.25
1-2-1	0.0	-0.2	1.1	13.07
1-2-2	0.0	0.0	1.1	12.17
1-2-3	0.0	0.2	1.1	14.19
1-3-1	0.2	-0.2	1.1	9.62
1-3-2	0.2	0.0	1.1	8.62
1-3-3	0.2	0.2	1.1	11.81
2-1-1	-0.2	-0.2	1.5	32.39
2-1-2	-0.2	0.0	1.5	52.54
2-1-3	-0.2	0.2	1.5	57.52
2-2-1	0.0	-0.2	1.5	32.44
2-2-2	0.0	0.0	1.5	48.25
2-2-3	0.0	0.2	1.5	54.20
2-3-1	0.2	-0.2	1.5	49.06
2-3-2	0.2	0.0	1.5	44.91
2-3-3	0.2	0.2	1.5	49.48
3-1-1	-0.2	-0.2	1.7	8.76
3-1-2	-0.2	0.0	1.7	15.47
3-1-3	-0.2	0.2	1.7	16.15
3-2-1	0.0	-0.2	1.7	9.55
3-2-2	0.0	0.0	1.7	16.29
3-2-3	0.0	0.2	1.7	16.80
3-3-1	0.2	-0.2	1.7	10.56
3-3-2	0.2	0.0	1.7	16.06
3-3-3	0.2	0.2	1.7	19.19
one point (2-2-2)	0.0	0.0	1.5	48.25
3 point average	0.0	0.0	1.5	30.23
9 point average	0.0	0.0	1.5	28.82
27 point average	0.0	0.0	1.5	29.55
9 point average 1.1 m	0.0	0.0	1.1	12.06
9 point average 1.5 m	0.0	0.0	1.5	47.50
9 point average 1.7 m	0.0	0.0	1.7	14.73

4.8 Scenario 8: Laboratory, Wi-Fi 6

A Wi-Fi 6 (IEEE 802.11ax) wireless local area network operating in the 5 GHz frequency band is deployed in a university laboratory with a total floor area of 63 m². The access point (AP) is positioned on top of a table at a height of approximately 1 m above the floor. The device operates with a maximum transmit power of 23 dBm (equivalent to 200 mW), providing wireless connectivity within the lab environment.



Figure 30: Measurements inside the laboratory

4.8.1 Detailed information regarding the installation

Detailed information regarding the installation is given in Table 29.

Table 29: Detailed information regarding the installation.

Location description	
type of location	Laboratory
type of installation	private operational site
AP's antenna parameters	
AP model	Cudy WR-1500
antenna type	4 element array
antenna gain [dBi]	4.43 per antenna element
location of antenna	on a table
antenna height (middle) [m]	1.06
antenna size [m]	≈0.18×0.12×0.03
downtilt [°]	0
envelope of radiation pattern in use	No beamforming
Transmission parameters	
Type	Wi-Fi 6
frequency band	5 GHz
central frequency [MHz]	5.2
channel number (center)	44
bandwidth [MHz]	20

MIMO configuration	2x2
max output power [W]	0.2
max output power [dBm]	23
duty cycle	-
Measurement conditions	
type of measurements	measurements under load

4.8.2 Results of raster measurements

Raster measurements were carried out to assess exposure levels under high-traffic conditions. A total of 88 measurement points were distributed within the laboratory's free space, with a spacing of 0.5 m between adjacent points. All measurements were taken at a sensor height of 1.1 m. To simulate maximum network activity, a controlled traffic load was generated using *iPerf3*. Unidirectional traffic was applied in UDP mode to maximize channel utilization by eliminating the error control and acknowledgment delays associated with TCP. The *iPerf3* server was a laptop connected to the router via Ethernet, while the client was a mobile device wirelessly connected to the access point. The measured electric field values are presented in Table 30.

Table 30: Results of raster measurements

Meas. point	x [m]	y [m]	E [V/m]	Meas. point	x [m]	y [m]	E [V/m]
1	6.41	1.16	0.85	45	3.41	2.16	0.87
2	6.41	1.66	0.92	46	3.41	1.66	0.99
3	6.41	2.16	0.69	47	2.91	1.66	1.1
4	6.41	2.66	0.8	48	2.91	2.16	1.2
5	6.41	3.16	0.6	49	2.91	2.66	1.2
6	6.41	3.66	1.6	50	2.91	3.16	1.4
7	6.41	4.16	0.9	51	2.91	3.66	1.4
8	6.41	4.66	0.7	52	2.91	4.16	1.7
9	6.41	5.16	0.7	53	2.91	4.66	1.5
10	6.41	5.66	1.1	54	2.91	5.16	1.9
11	6.41	6.16	0.9	55	2.91	5.66	1.6
12	5.91	6.16	0.8	56	2.91	6.16	1.3
13	5.41	6.16	0.8	57	2.41	6.16	1.6
14	4.91	6.16	1.4	58	2.41	5.66	1.3
15	4.41	6.16	1.7	59	2.41	5.16	2.3
16	3.91	6.16	1.3	60	2.41	4.66	1.8
17	5.91	5.66	0.6	61	2.41	4.16	1.3
18	5.41	5.66	1.3	62	2.41	3.66	2.2
19	4.91	5.66	1.3	63	2.41	3.16	1.6
20	4.41	5.66	1.3	64	2.41	2.66	1.4
21	3.91	5.66	0.9	65	2.41	2.16	1.2
22	5.91	5.16	1	66	2.41	1.66	1
23	5.41	5.16	0.8	67	1.91	0.66	1.5
24	4.91	5.16	1	68	1.91	1.16	0.93
25	4.41	5.16	1	69	1.91	1.66	1.3
26	3.91	5.16	1.3	70	1.91	2.16	1.5
27	5.91	4.66	0.6	71	1.91	2.66	1.4
28	5.41	4.66	0.7	72	1.91	3.16	1.2

29	4.91	4.66	0.8	73	1.91	3.66	1.5
30	4.41	4.66	1.2	74	1.91	4.16	2.7
31	3.91	4.66	1.3	75	1.91	4.66	2.7
32	5.91	1.66	0.9	76	1.91	5.16	2.4
33	5.41	1.66	0.9	77	1.91	5.66	2
34	4.91	1.66	0.9	78	1.91	6.16	2.2
35	4.41	1.66	1.2	79	2.41	5.16	3.6
36	3.91	1.66	1.1	80	2.41	4.66	5.2
37	3.41	6.16	1.3	81	2.41	4.16	4
38	3.41	5.66	0.99	82	2.41	3.66	2.6
39	3.41	5.16	1.3	83	2.41	3.16	1.8
40	3.41	4.66	1.1	84	2.41	2.66	2.3
41	3.41	4.16	1.4	85	2.41	2.16	1.9
42	3.41	3.66	1.2	86	2.41	1.66	1.3
43	3.41	3.16	0.9	87	2.41	1.16	1
44	3.41	2.66	1.2	88	2.41	0.66	0.8

Table 31: Statistics for raster measurements.

result type	E [V/m]
maximum value	5.20
95th percentile	2.67
mean value	1.58
median value	1.30
standard deviation	1.90
Variance	0.54

In the 2D spatial plot of Figure 31, the location of measurement points and the transmitter are presented. The position of each circle represents the (x, y) location, and its color corresponds to the measured electric field strength.

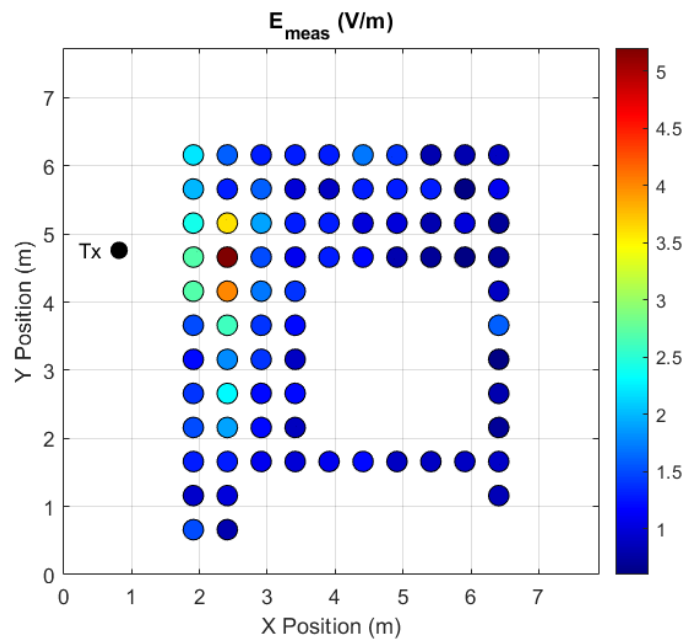


Figure 31: Location of measurement points and E-field values

In Figure 32, the statistical distribution of the measured values is depicted with a Cumulative Distribution Function (CDF) plot.

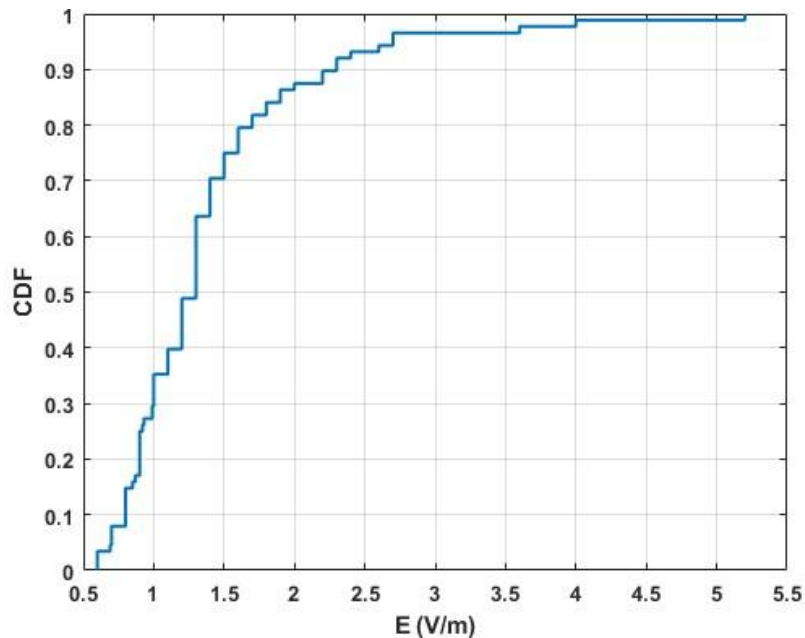


Figure 32: Cumulative Distribution Function (CDF) of the measured electric field values across all 88 locations.

4.9 Scenario 9: Smart Industry 4.0: Industrial-outdoor environment, private 5G FR1

We measured the RF EMF exposure induced by a private 5G wireless access network in an outdoor industrial environment in Belgium. The area consisted of open space as well as cluttered areas with large and irregular shaped buildings. The network operated in the FR1 frequency range and consisted of several multiband base station antennas. Both omnidirectional and sector antennas were installed to provide coverage and bandwidth throughout the entire industrial site. We measured the exposure induced by the private network operator in band n7 (2600 MHz) and band n78 (3500 MHz) during an FTP speedtest to a connected smart phone. Measurement locations were all outdoor in LOS and NLOS of the base station antennas.

4.9.1 Information regarding the installation

The private 5G network operating in the FR1 frequency range consisted of several multiband base station antennas deployed in the area. Both omnidirectional and sector antennas were installed to provide coverage and bandwidth throughout the entire industrial site.

Table 32: Information regarding the installation.

Location description	
type of location	Industrial, outdoor environment
type of installation	private 4G and 5G network
AP's antenna parameters	
AP model	-
antenna types	Omnidirectional, multiband sector, and beamforming antenna
antenna gain [dBi]	9 – 18.5 dBi
location of antenna	outdoor
antenna height (middle) [m]	-
antenna size [m]	-
downtilt [°]	-
envelope of radiation pattern in use	-
Transmission parameters	
Type	4G-LTE in band n7 (2600 MHz) and 5G-NR in band n78 (3500 MHz)
frequency band	2600 MHz (n7) and 3500 MHz (n78)
central frequency [MHz]	-
channel number (center)	-
bandwidth [MHz]	-
MIMO configuration	-
max output power [W]	-
max output power [dBm]	-
duty cycle	-
Measurement conditions	
type of measurements	measurements under load

4.9.2 Results of line measurements

We performed exposure measurements in an open area and, thus, in LOS of a multiband base station antenna with increasing distance between measurement location and base station antenna location.

The separation varied between 200 m and 430 m. Figure 33 shows the measured RMS E-field during an FTP download in the LTE band at 2600 MHz and the NR band at 3500 MHz. RMS E-field in the LTE band at 2600 MHz (0.62 V/m – 1.42 V/m) was larger than the RMS E-field at 3500 MHz (0.13 V/m – 0.14 V/m). The RSM E-field showed a constant value over the measured locations at 3500 MHz, whereas at 2600 MHz the RMS E-field showed the lowest value at 194 m and the largest value at a distance of 315 m.

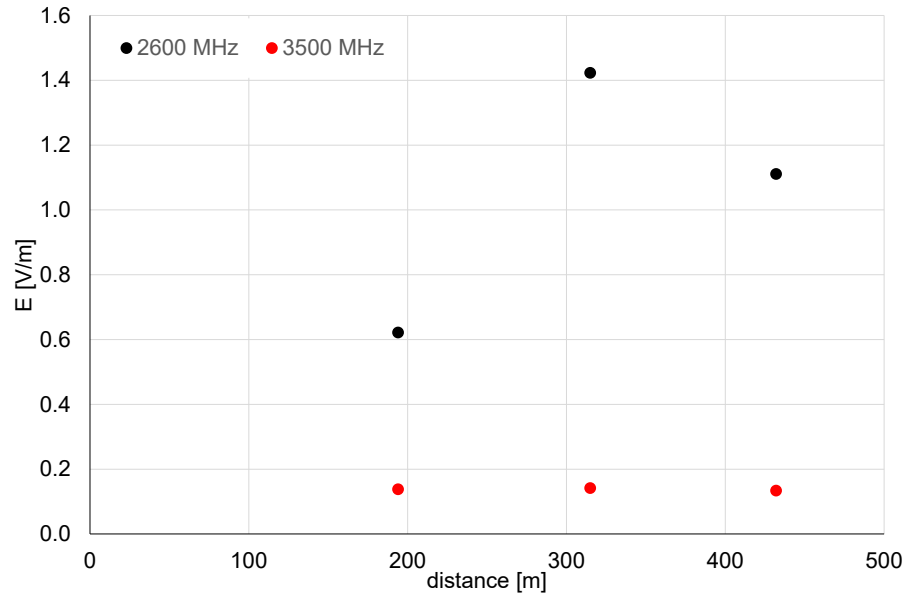


Figure 33: Results for line measurements in the LTE band at 2600 MHz and 5G-NR band at 3500 MHz. All measurements were done at a height of 1.5 m.

Table 33: Results for line measurements in the LTE band at 2600 MHz and 5G-NR band at 3500 MHz.

distance [m]	$E_{2600\text{ MHz}}$ [V/m]	$E_{3500\text{ MHz}}$ [V/m]
194.0	0.62	0.14
315.0	1.42	0.14
432.0	1.11	0.13

4.9.3 Results of spatial measurements

We measured the max E-field at eight locations in the industrial-outdoor environment during an FTP download with a smartphone at two meters from the measurement probe. In LOS, the exposure by LTE at 2600 MHz is up to 10 times larger than the exposure in the 3500 MHz band. For locations in NLOS exposure values at 2600 MHz and 3500 MHz are in the same order of magnitude.

Table 34: Results of spatial measurements.

measurement location	distance to base station [m]	$E_{2600\text{ MHz}}$ [V/m]	$E_{3500\text{ MHz}}$ [V/m]
1	589.0	0.40	0.08
2	253.0	0.06	0.02
3	165.0	0.09	0.06
4	182.0	0.06	0.11
5	87.0	0.11	0.11
6	194.0	0.62	0.14
7	315.0	1.42	0.14
8	432.0	1.11	0.13
95th percentile		1.32	0.14
median value		0.29	0.11
standard deviation		0.87	0.09
variance		0.28	0.00

4.10 Scenario 10: Smart Industry 4.0: Pallet warehouse, private 5G FR1

Fabriek Logistiek is a logistics test center in Ghent, Belgium, consisting of a pallet warehouse of 2400 m² and an eCommerce warehouse of 2000 m². In the entire test center a 5G private network has been deployed by a mobile operator. We have measured the exposure in terms of RMS E-field and the path loss in the pallet warehouse. This warehouse contains six 4G/5G directional 4x4 MIMO in-building antennas needed to provide coverage in each of the corridors between the metal racks of the pallet warehouse (see Figure 34).



Figure 34: Picture of the metal racks in the pallet warehouse.

4.10.1 Information regarding the private 5G installation

Information on the installation is given in Table 35.

Table 35: Information regarding the installation in the pallet warehouse.

Location description	
type of location	industrial, indoor environment
type of installation	private 4G and 5G network
AP's antenna parameters	
AP model	-
antenna types	4G/5G directional 4X4 MIMO
antenna gain [dBi]	9 – 18.5 dBi
location of antenna	indoor
antenna height (middle) [m]	-
antenna size [m]	-

downtilt [°]	-
envelope of radiation pattern in use	-
Transmission parameters	
Type	LTE / 5G-NR
frequency band	n7 and n78
central frequency [MHz]	2600 MHz and 3700 MHz
channel number (center)	-
bandwidth [MHz]	-
MIMO configuration	4x4
max output power [W]	-
max output power [dBm]	-
duty cycle	-
Measurement conditions	
type of measurements	measurements under load

4.10.2 Results of raster measurements

4.10.2.1 Exposure assessment

The exposure assessment setup consisted of the NARDA SRM-3006 and the triaxial, frequency selective probe for frequencies between 30 MHz and 6 GHz. The center of the probe was positioned at a height of 1.7 m. The smartphone, a Xiaomi 12 Pro equipped with the drive test tool QualiPoc was located at 2 m from the probe. Two scenarios were considered: idle scenario during which no active downlink connection was established during the measurement and the “FTP 10 GB download” initiated by and running on the Xiaomi Pro 12 during measurement (see Figure 35).

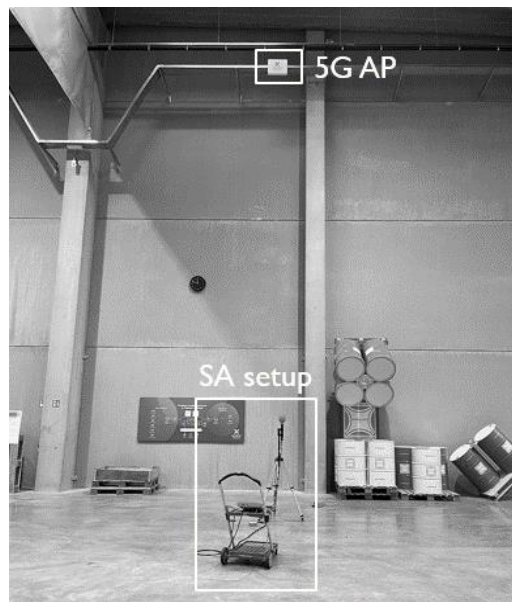


Figure 35: The spectrum analyzer (SA) setup consisting of the NARDA SRM-3006 and tri-axial probe, the smartphone on the trolley, and the 5G access point installed close to the roof of the pallet warehouse.

Table 36 lists the mean and maximum RMS E-field values measured in the 3700-3800 MHz band at nine locations in the pallet warehouse. The mean RMS E-field for the “Idle” scenario measured between 0.13 V/m and 0.14 V/m. During the “FTP 10 GB DL” scenario, the mean RMS E-field ranged from 0.24 V/m at locations Loc 2 and Loc 5 to 0.41 V/m at location “Loc 9”. The maximum measured RMS E-field values observed during the “FTP 10 GB DL” scenario were 3.5 to 3.8 times higher than the mean values, ranging from 0.77 V/m at location Loc 5 to 1.56 V/m at location Loc 9. For the “Idle” scenario, the maximum values ranged from 0.51 V/m at location Loc 5 to 1.00 V/m at location Loc 6.

Table 36: Mean and maximum RMS E-field measured in the frequency band 3700 - 3800 MHz at nine locations in the pallet warehouse for "Idle" (background) and “FTP 10 GB download” scenarios.

measurement location	$E_{\text{Idle AVG}}$ [V/m]	$E_{\text{Idle MAX}}$ [V/m]	$E_{\text{FTP DL 10 GB AVG}}$ [V/m]	$E_{\text{FTP DL 10 GB MAX}}$ [V/m]
1	0.13	0.76	0.34	1.16
2	0.13	0.74	0.24	0.92
3	0.14	0.65	0.34	1.10
4	0.14	0.78	0.36	1.29
5	0.13	0.51	0.24	0.77
6	0.14	1.00	/	/
7	0.14	0.85	0.36	1.24
8	0.14	0.82	0.36	1.28
9	0.14	0.95	0.41	1.56
95th percentile	0.14	0.98	0.39	1.47
median value	0.13	0.74	0.32	1.05
standard deviation	0.03	0.48	0.19	0.75
variance	0.00	0.02	0.00	0.06



Figure 36: Measured averaged RMS E-field between 3700 MHz and 3800 MHz for the "Idle" (background) scenario in the pallet warehouse plotted on the ground plan of the pallet warehouse. The locations of the access points are indicated by the label "Loc" followed by a number. The RMS E-field values are represented as circles with color and radius scaled according to the field value.

Figure 36 and Figure 37 show the mean RMS E-field in the 3700-3800 MHz frequency band on a ground plane of the pallet warehouse for "Idle" (background) scenario and "FTP 10 GB DL" scenario. The 3700-3800 MHz is the frequency band operated by the 5G private network.

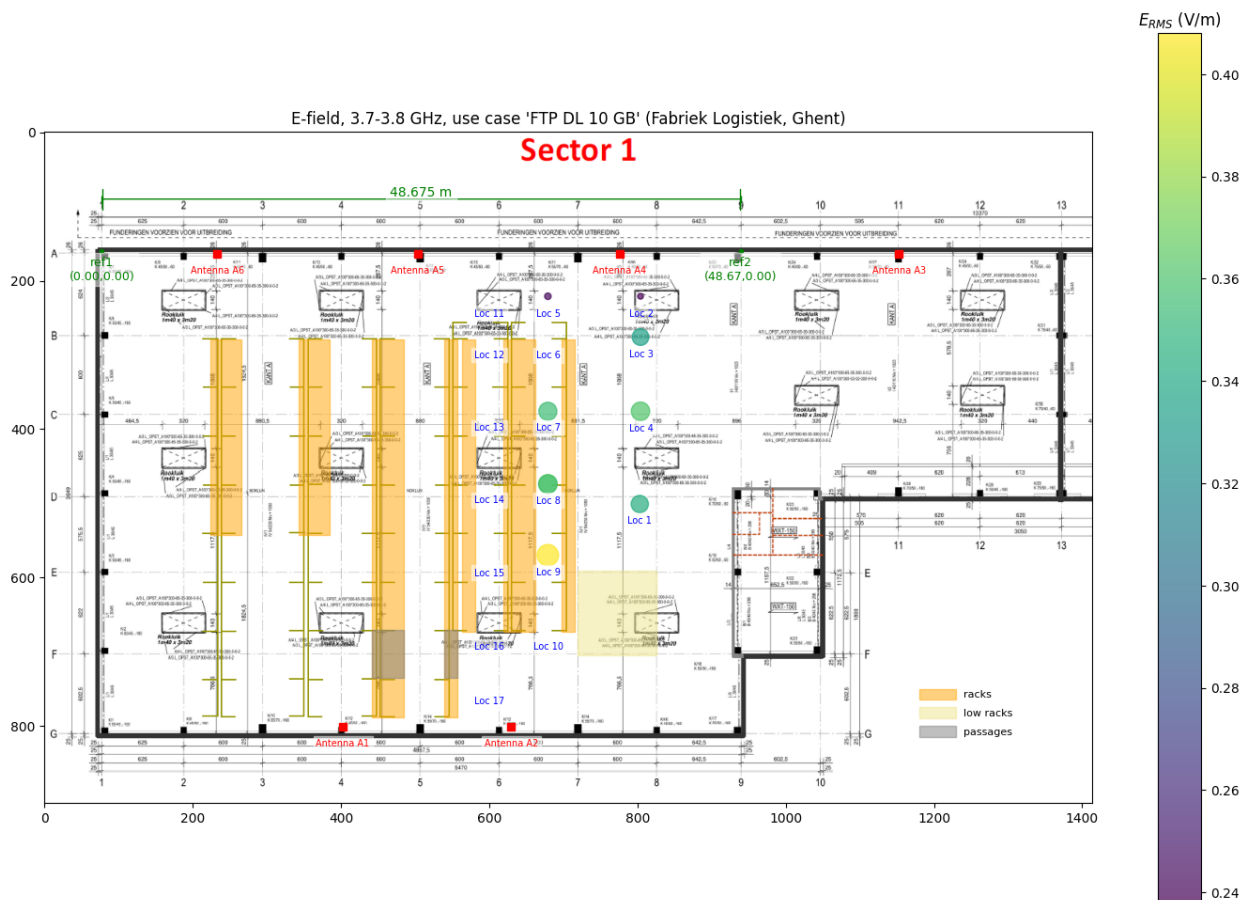


Figure 37: Measured averaged RMS E-field between 3700 MHz and 3800 MHz for the "FTP 10 GB download" scenario in the pallet warehouse plotted on the ground plan of the pallet warehouse. The location of the access points are indicated by the label "Loc" followed by a number. The RMS E-field values are represented as circles with color and radius scaled according to the field value.

5 Exposure due to IOT devices

5.1 Industrial gateway, 5G FR1

The industrial gateway with a maximum output power of 200 mW operates in the frequency band 3.5 GHz. It uses 20 MHz bandwidth. During measurements, it was connected to a private standalone network, and a speed test was carried out ensuring maximum transmit power. However, the gateway was set to operate at a maximum power of 80 mW. The gateway was connected to an external directional antenna. Measurements were performed in the main direction at distances of 0.2, 0.3 and 0.5 m as well as perpendicular to the main direction at the distance of 0.2 m. Measurements were done with a broadband probe.



Figure 38: Equipment under test.

In Table 37 the measured values are given for output power of modem 80 mW as well as the extrapolated values for full power of 200 mW are given.

Table 37: Results of measurement of industrial gateway at 80 mW and extrapolated values to 200 mW. Measurements were made in the direction of the main beam of the antenna and perpendicular to the main beam.

<i>distance</i> [m]	<i>E</i> _{broadband 80 mW} [V/m]		<i>E</i> _{broadband 200 mW} [V/m]	
	main beam	perpendicular to main beam	main beam	perpendicular to main beam
0.2	7.5	7.5	11.9	7.9
0.3	4.2	4.2	6.6	
0.5	2.0	2.0	3.2	

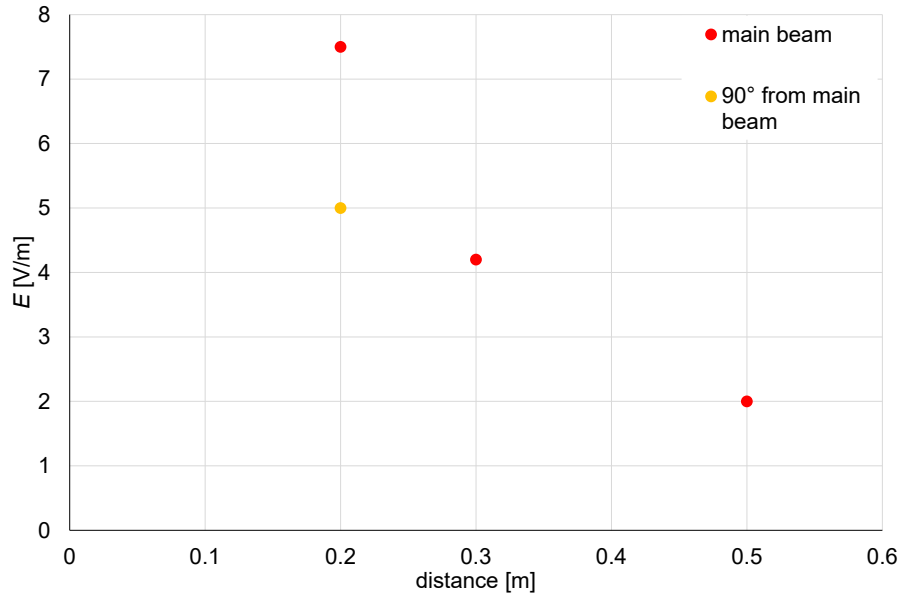


Figure 39: Results for measurement of industrial gateway at 80 mW. Measurements were done in the direction of the main beam of the antenna and perpendicular to the main beam.

5.2 Gateway, 5G FR1

The industrial and home use gateway Innbox W37 with a maximum output power of 200 mW operates in the frequency band 3.5 GHz. It uses 100 MHz bandwidth. During measurements, it was connected to a private standalone network, and a speed test was carried out ensuring maximum transmit power. The gateway has internal antennas. Measurements were performed in the main direction and perpendicular to the main direction at distances of 0.2, 0.4, 0.6, 0.8 and 1 m. Measurements were done with a broadband probe.



Figure 40: Equipment under test.

Table 38: Results of measurement of industrial gateway. Measurements were done in the direction of the main beam of the antenna and perpendicular to the main beam.

<i>distance [m]</i>	<i>E_{broadband} [V/m]</i>	
	main beam	perpendicular
0.2	3.1	2.6
0.4	1.7	1.4
0.6	1.8	0.8
0.8	1.4	0.7
0.2	3.1	2.6

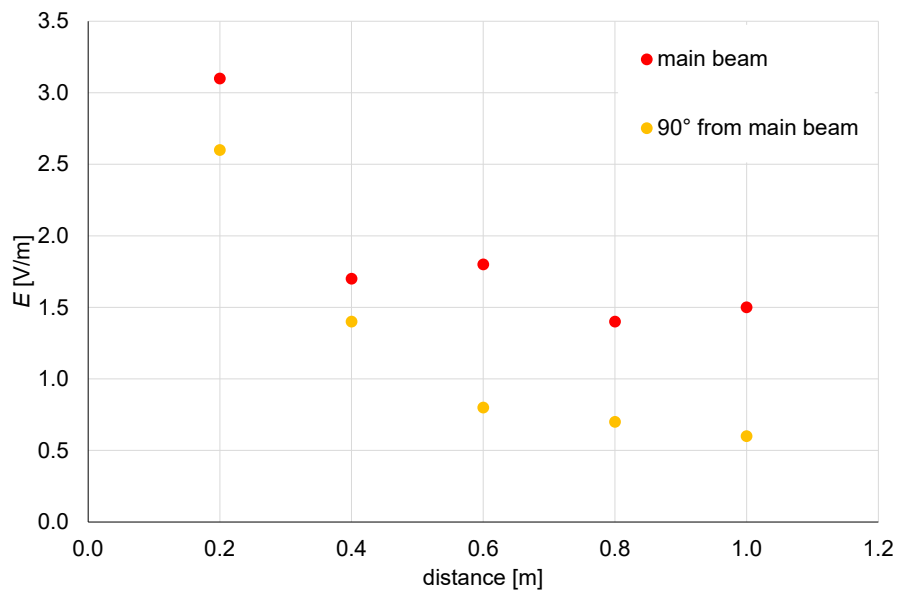


Figure 41: Results for measurement of industrial modem. Measurements were made in the direction of the main beam of the antenna and perpendicular to the main beam.

5.3 Surveillance camera, 5G FR1

The industrial and home use surveillance camera Milesight Network camera MS-C5366 was installed on the wall of the entrance hall of a building at the height of 2.5 m. During measurements, it was connected to a private standalone network operating at a frequency of 3400 to 3500 MHz. The camera had 4 external antennas. Measurements were performed at the height of the camera at distances of 0.2, 0.5, 1 and 2 m from the camera and below the camera at the same distances. Measurements were performed as broadband measurements at normal working conditions when the camera was constantly streaming video generating between 300 and 500 kbps of upload traffic.

Table 39: Results of measurement of industrial surveillance camera. Measurements were done in the height of camera and below the camera.

distance [m]	$E_{broadband}$ [V/m]	
	in the height of camera	below camera
0.2	2.77	2.36
0.5	1.42	1.70
1.0	0.71	1.15
2.0	0.34	0.27

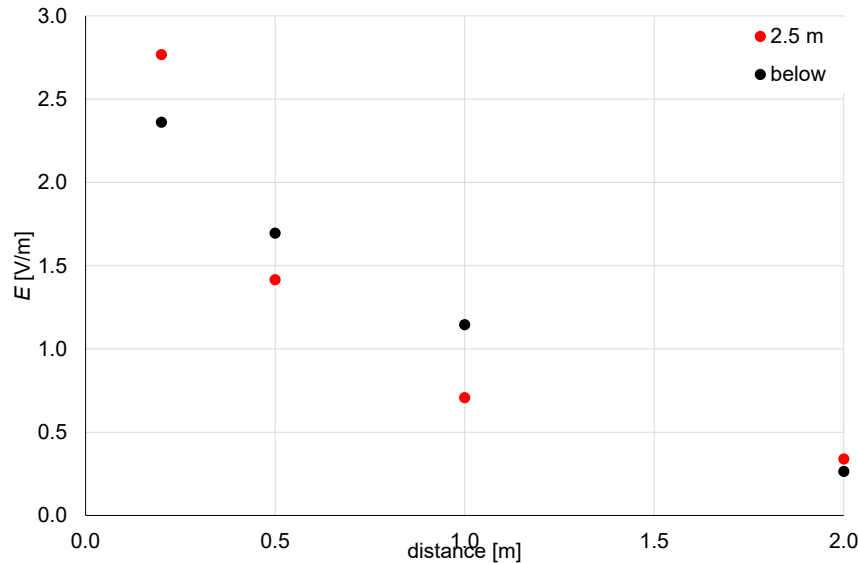


Figure 42: Results for measurement of industrial surveillance camera. Measurements were done at different distances from the camera, once at the height of the camera 2.5 m above floor level and once in a vertical line below the camera.

5.4 Terberg terminal tractor, 5G FR1

Terbeg terminal tractors are used in Port of Koper to move goods inside the port. As a measured example, an industrial gateway with a maximum output power of 200 mW is installed with 4 output antennas, some of them installed inside the cabin and some on the cabin roof. The gateway operates in the frequency band 3.5 GHz. It uses 100 MHz bandwidth. During measurements, it was connected to a slice of a public 3.5 GHz network operating between 3420 and 3520 MHz.

Table 40: Results of measurement inside the cabin of the terminal tractor.

$E_{broadband}$ [V/m]	driver	passenger
maximum value	2.60	2.65
95th percentile	1.55	1.35
mean value	0.63	0.58
maximum 6 minute mean value	0.64	0.58
median value	0.09	0.10
standard deviation	0.98	0.90
Variance	0.27	0.22

Measurements were made for normal working conditions, meaning there was an active video stream running from the Terberg terminal tractor to the network as well as active transfer of live vehicle status and diagnostic data. Measurements were performed on the position of the driver and co-driver inside the cabin of the terminal tractor for a period of 10 minutes.



Figure 43: Measurements inside the cabin of the terminal tractor.

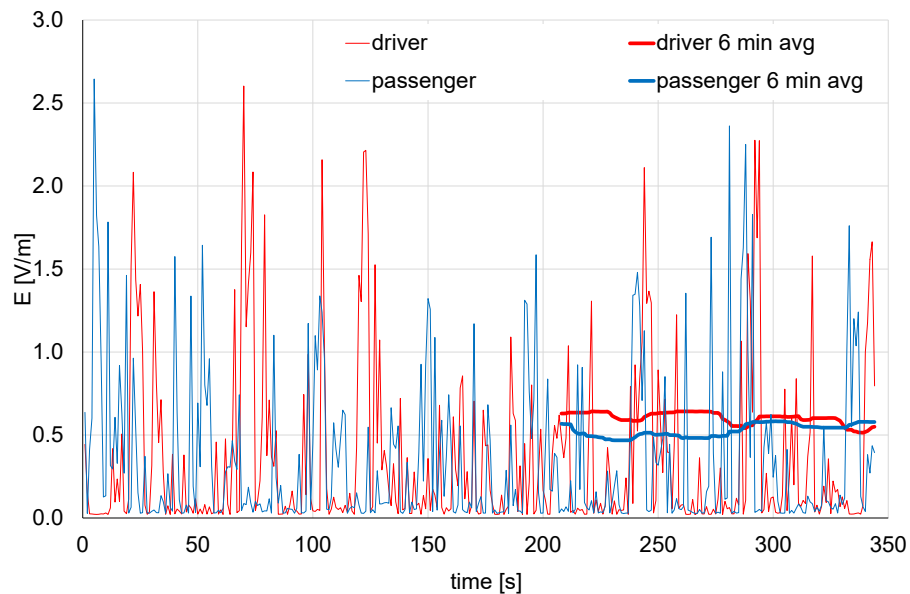


Figure 44: Measurement results inside the terminal tractor in the driver and passenger positions.

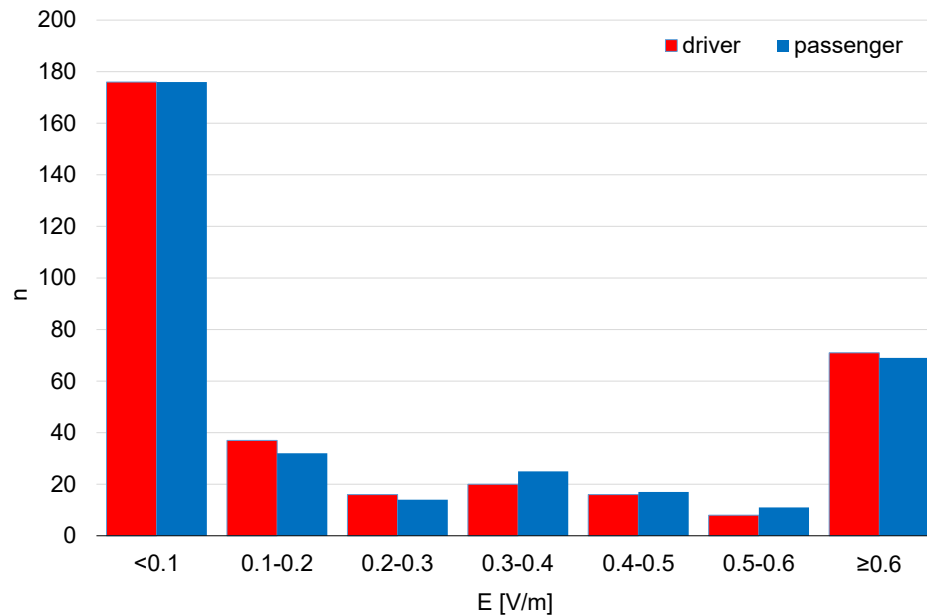


Figure 45: Histogram of the measurements inside the cabin of the terminal tractor on the driver and passenger positions.

5.5 Mobile camera setup and smartphone, 5G FR1

In the industrial environment in Belgium a mobile camera setup is used for surveillance of workers during working activities. The mobile camera setup consisted of a camera installed on a tripod and a protector case in which the antennas were installed. We measured the RMS E-field as function of the distance to the mobile camera using a frequency selective measurement setup consisting of the NARDA SRM-3006 and a tri-axial probe (30 MHz – 6 GHz). Figure 46 shows the measured uplink exposure in terms of RMS E-field as a function of distance between 50 cm and 3 m. The mobile camera system was continuously streaming during the measurement. For the smartphone iPerf was used to generate an uplink data stream. We observed that mobile camera was only transmitting in the 2600 MHz band. The averaged RMS E-field during video streaming was significantly lower than the exposure induced by the iPhone running iPerf and decreased with distance (0.06 V/m at 50 cm to 0.01 V/m at 3 m). The smartphone running iPerf was mainly transmitting in the 3500 MHz band with values ranging from 0.46 V/m at 50 cm to 0.25 V/m at 3 m.

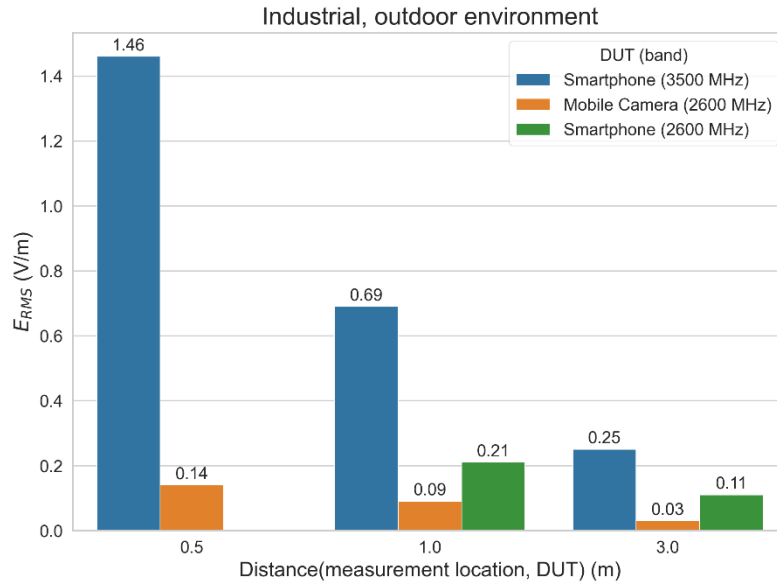


Figure 46: Measured RMS E-field of the uplink of a mobile camera system and a smartphone operating in the 2600 MHz band (n7) and 3500 MHz band (n78). The measurement probe was vertically aligned with the center of the DUT. The distance was measured from the front of the device to the center of the measurement probe.

6 Conclusion

RF EMF measurements were carried out across a total of 10 different scenarios. When selecting these scenarios, special attention was given to ensuring diversity. Consequently, the measurements covered different sectors (e.g., logistics, manufacturing, offices), different emerging technologies (5G, Wi-Fi 6), and various frequency bands (3.5 GHz, 5 GHz, 26 GHz). The private network settings were also differed, ranging from a public slice of a macrocell on a pole operating at 100 W per sector to picocells with power below 1 W mounted on ceilings.

The selection process, however, was significantly complicated by several unforeseen external factors. The first was the limited availability of real private 5G installations. The deployment of 5G in Industry 4.0 progressed much more slowly than anticipated at the start of the project in 2022, and thus only a small number of private 5G networks were operational before 2024 in the area where consortium members had access to the smart Industries facilities. Second, the owners of the few existing private 5G installations were generally unwilling to grant external access to their facilities, preventing measurement campaigns.

Another major challenge was the lack of traffic. Most private 5G networks are currently either completely idle or carry very limited traffic, especially in terms of the number of connected devices. While 5G in Industry 4.0 is intended to wirelessly connect large numbers of IIoT devices and sensors including user interfaces, in practice only a few devices were connected during the measurements.

Nevertheless, time-variability measurements were performed in key analyzed scenarios. These included both pilot signals and the total value across the frequency band in which the network was operating. In cases where traffic was present—or deliberately generated—some information on time variability and average exposure could be obtained. However, estimating the expected average exposure values in private 5G networks remains highly constrained by the current limited operational state of such networks.

To address this, worst-case conditions were determined in all measurement scenarios, either by selective measurements with extrapolation to maximum values or by performing measurements under forced traffic conditions (e.g., speed tests or continuous data transfer).

Table 41 summarizes all raster measurement results. Raster measurements were chosen because they provide the best estimate of the RF EMF levels emitted by the equipment under test. Since raster measurement points were distributed throughout the entire area surrounding the source, they also offered a reliable estimate of the average RF EMF exposure of workers in the vicinity of the private wireless network applied in smart Industries.

Table 41: Overview of results of all raster measurements.

scenario \ type of result	E [V/m]			σ^2 [V ² /m ²]
	95th percentile	median value	standard deviation	Variance
1: Logistic sector: Port of Koper, private 5G FR1 macro cell	21.97	2.28	16.02	89.38
2: Logistic sector: Port of Koper, public slice 5G FR1 macro cell	20.82	11.14	12.98	47.09
3: Smart IOT solutions: warehouse, private 5G FR1 micro cell	1.01	0.39	0.64	0.09
4: Smart IOT solutions: production site, private 5G FR1 micro cell	1.22	0.66	0.88	0.12
5: Office, test facility of wireless networks, private 5G FR1 micro cell	10.74	5.05	6.46	8.17
6: Office, production site, private 5G FR1 pico cell	4.07	1.05	2.90	2.36
7: Research facility private 5G FR2 micro cell	48.44	11.69	33.73	275.39
8: Laboratory Wi-Fi 6	2.67	1.30	1.90	0.54
9: Industrial outdoor environment, private 5G FR1	0.14	0.11	0.09	0.00
10: Smart Industry 4.0: Pallet warehouse, private SA 5G FR1 micro cell	1.47	1.20	0.75	0.06

From the results in Table 41, it can be observed that the statistical values show substantial variability across different exposure scenarios, with differences of up to a factor of 20. Spatial variability of the measured values is also evident. For scenarios 2, 3, 4, 5, and 8, the ratio between the median and maximum values is below 4, indicating that measurement points in these scenarios did not differ significantly. In contrast, in scenario 1 the ratio exceeds 10, suggesting the presence of a strong outlier skewing the results. In this case, the antenna was installed at a height of only 1.9 m, which meant that the closest measurement point was located directly in the main beam and at a short distance from the antenna.

The investigation of time variability demonstrated that the averaging time has little effect when performing selective measurements. In the four cases analyzed, the maximum difference between the 1-minute and 6-minute averages was 33%, and below 10% when comparing the 3-minute average.

By contrast, when measuring the entire 5G band, the differences were substantially larger due to the operating conditions of the network under test. Although the base stations were operational, they carried traffic only for a small fraction of the time. As a result, intermittent high values had a strong impact on the average. The maximum difference between 1-minute and 6-minute averages reached 100%. Significant differences were also observed between periods of speed testing and idle periods.

For example, in scenario 5 (Office, wireless network test facility), the only connected device was the modem used for the speed test, which included both download and upload phases. The measured values during these periods differed markedly from those obtained in idle times. A similar pattern was seen in scenario 1 (Logistics sector, Port of Koper), where during low-traffic periods the electric field was only slightly above 1 V/m, but rose to 2.5–5 V/m when traffic was present.

Spatial variability was also assessed for several exposure scenarios. Measurements followed the IEC 62232:2022 [3] scheme for spatial averaging at three heights (1.1 m, 1.5 m, 1.7 m) and three

lateral positions (center, 0.2 m left, 0.2 m right), yielding nine measurements. Two additional vertical planes (0.2 m in front and 0.2 m behind) increased the total to 27 measurement points.

Based on these, the following averages were calculated:

- **1-point value:** central point at 1.5 m
- **3-point average:** central points at 1.1 m, 1.5 m, and 1.7 m
- **9-point average (vertical plane):** points at 1.1 m, 1.5 m, 1.7 m in the central plane
- **27-point average:** all measurement points
- **9-point average at 1.1 m, 1.5 m, and 1.7 m:** all points at each respective height

In scenario 2 (Logistics sector, Port of Koper), the source was a private slice of a 5G network using a beamforming macrocell mounted on a pole. All averaging schemes yielded similar values for the pilot signal: individual measurements ranged from 0.095 to 0.228 V/m, while averages ranged from 0.136 to 0.151 V/m. Variability of extrapolated maximum values was larger due to beamforming effects. Despite the close spatial clustering of measurement points, the extrapolation factor varied between 215.28 and 270.56. Extrapolated values ranged from 20.80 to 48.99 V/m, while averaged values ranged from 32.27 to 36.42 V/m. The differences between averaging methods were not significant.

Similar findings were obtained for scenario 5 (Office, wireless network test facility), where the lowest value was 9.35 V/m (single point), and the highest was 12.71 V/m (3-point average).

In contrast, scenario 7 (Research facility with FR2 beamforming radio head) showed significant variation between averaging methods, which was heavily influenced by measurement height. This was expected due to the short distance between the measurement point and highly directive base station antenna. Minor changes in antenna height caused large fluctuations in antenna gain and, consequently, in the electric field strength. The maximum single-point value was 48.55 V/m, while the minimum—the 9-point average at 1.1 m—was 12.16 V/m. The effect of height is clearly demonstrated by the 9-point averages: at 1.5 m it was 47.50 V/m, but at 1.7 m it dropped sharply to 14.73 V/m.

7 Appendix

7.1 List of abbreviations

ABBREVIATION	MEANING
3G	Third generation of broadband cellular network technology
3GPP	3rd Generation Partnership Project
4G	Fourth generation of broadband cellular network technology
5G	Fifth generation of broadband cellular network technology
5G NR	5G New Radio
5GAA	5G Automotive Association
5G-ACIA	5G Alliance for Connected Industries and Automation
AGV	Automated Guided Vehicles
AMR	Autonomous Mobile Robot
AMR	Autonomous Mobile Robots
APN	Access Point Name
BSS	Basic Service Set
dBi	Antenna gain in decibels relatively to isotropic antenna
DSS	Dynamic Spectrum Sharing
eDRX	Extended Discontinuous Reception
EIRP	Equivalent Isotropically Radiated Power
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
eNodeB	Evolved Node B in 4G radio
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FR1	Frequency Range 1
FR2	Frequency Range 2
gNB	Next Generation Node B
gNodeB	Next Generation Node B
GSA	Global mobile Suppliers Association
ICT	Information and Communications Technology
LAN	Local Area Network
LTE	Long Term Evolution Technology
LTE-A	LTE-Advanced
LTE-A Pro	LTE-Advanced Pro
LTE-M	Long Term Evolution for Machines
M2M	Machine to Machine
MIMO	Multiple-Input Multiple-Output
MMS	Multi Media Service
mMTC	Massive Machine Type Communications
mmWave	millimeter wave
mTRP	Multiple Transmission and Reception Point
MU-MIMO	MU-MIMO
NB-IoT	Narrow Band IoT
NSA	Non-Standalone
OBSS	Overlapping Basic Service Sets
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OT	Operational Technology
pLTE	Private LTE Network
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RF	Radio Frequency
SA	Standalone
SMS	Short Messaging Service
SNR	Signal to Noise ratio
TCO	total cost of ownership
TDD	Time Division Duplex
UE	User Equipment
URLLC	Ultra Reliable Low Latency Communications
VoLTE	Voice over LTE
VPN	Virtual Private Network

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