ECC Report 345

In-band measurement methodologies for 5G AAS base stations in the field

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0 EXECUTIVE SUMMARY

Emission limits for 5G stations using active antenna systems (AAS) are often defined as total radiated power (TRP). In order to enforce these limits, as well as for other purposes such as interference investigation and cross-border coordination, administrations need to measure emissions from 5G AAS stations. However, AAS usually do not provide a test point which could be used to make conducted measurements. It is therefore necessary to measure the emissions (in-band as well as unwanted) over the air, which is especially challenging due to the dynamic properties of 5G signals and the fact that antenna characteristics and directions are not fixed.

This Report summarises the current knowledge and suggests possible ways to measure in-band emissions of 5G AAS base stations over the air, including methods to derive e.i.r.p. and TRP. Specific examples of practical measurements are described which may serve as proofs of concept for the following measurement methods:

- Ground-based measurement of the broadcast and synchronisation signal in normal operating mode of the base station;
- Airborne measurement of the broadcast and synchronisation signal as well as the traffic signals with a drone while the base station is in a test mode, over a static beam;
- Ground-based measurement by attracting a traffic beam with an active user equipment while the base station is in normal operating mode.

Experience from the example field measurements and simulation above has shown that the concepts work practically and may provide results with reasonable accuracy. However, there is no single measurement method to be recommended. The most appropriate method in a specific case depends on

- the purpose of the measurement and required parameter (e. g. field strength, e.i.r.p. or TRP);
- possible modes of the base station (normal operation or test mode/test signal);
- available information on certain base station parameters (antenna directivity, beamset and pattern);
- local restrictions (surrounding environment, buildings, legal constraints regarding drone operation);
- available measurement equipment (analysers, decoding receivers/loggers, drones).

The possibilities to measure unwanted emissions are further limited, among others, by the fact that for enforcement of limits the base station needs to transmit at full power and bandwidth, which cannot be guaranteed during normal operation. However, a suitable test mode or test signal is currently not defined in the 3GPP specifications. Furthermore, the antenna gain and patterns in the unwanted frequency domains are not known, but this knowledge is one of the prerequisites of most measurement methods described. Therefore, this Report is limited to in-band measurements only.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
3GPP	3rd Generation Partnership Project
AAS	Active Antenna System
AAU	Active Array Unit
BS	Base Station
CATR	Compact Antenna Test Range
CEPT	European Conference of Postal and Telecommunications Administrations
EC	European Commission
ECC	Electronic Communications Committee
e.i.r.p.	Equivalent Isotropically Radiated Power
ETSI	European Telecommunications Standards Institute
EU	European Union
FSL	Free Space Loss
GNSS	Global Navigation Satellite System (GPS/BeiDou/Galileo/GLONASS)
HPBW	Half Power Beamwidth
LoS	Line of Sight
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OTA	Over-the-Air
RB	Resource Block
RBW	Resolution Bandwidth
RE	Resource Element
RF	Radio Frequency
RPE	Radiated Pattern Envelope
RSRP	Reference Signal Received Power
SSB	Synchronisation Signal Block
TA	Test Antenna
TRP	Total Radiated Power
UE	User Equipment

1 INTRODUCTION

There are occasions where administrations need to perform over-the-air measurements of radio devices such as mobile base stations deployed in the field. This can be for a variety of reasons including for example as detailed in section 3.2:

- Checking that the radio device meets its licence conditions;
- Part of interference investigations;
- Cross-border coordination.

New 5G Active Antenna Systems (AAS) can employ dynamic beamforming with limits prescribed in Total Radiated Power (TRP). This makes it more challenging to perform off-air measurements than for older technologies, where the beam was static, and the limits were prescribed in e.i.r.p.

Over-the-air (OTA) field measurements are separate from the issue of conformance testing which is normally carried out in a laboratory in accordance with relevant ETSI Harmonised Standards.

This ECC Report outlines techniques and methodologies to determine or estimate TRP (with equivalent measurement metrics) by field measurements for in-band emissions of 5G AAS, in order to facilitate administrations checking compliance with national regulations and performing interference investigations.

The power limits for base stations equipped with AAS are often prescribed in TRP that is defined as the integral of the power transmitted in different directions over the entire radiation sphere.

OTA measurements in the field are generally complex due to uncertainties caused by real life variables. Dynamic performance of AAS depends on factors such as:

- Real traffic condition (Number of active UEs, traffic load, etc);
- Propagation environment (multipath, weather, etc);
- Dynamic adjustment of traffic beam characteristics and direction:
- Relevant 5G BS characteristics.

The possibilities to measure unwanted emissions are further limited by, among others, the fact that for enforcement of limits the base station needs to transmit at full power and bandwidth, which cannot be guaranteed during normal operation. However, a suitable test mode or test signal is currently not defined in the 3GPP specifications. Furthermore, the antenna gain and patterns in the unwanted frequency domains are not known, but this knowledge is one of the prerequisites of most measurement methods described in this Report.

Therefore, this Report is limited to in-band measurements only.

2 DEFINITIONS

Term	Definition
Beamwidth	The beamwidth, or “half-power beamwidth” HPBW is defined as the angular region where the radiated power density is 3 dB below the power density in the direction of maximum gain.
Directivity	The directivity of an antenna in a certain direction is the power density of the antenna in this direction of radiation in three-dimensional space divided by its average power density. If the direction is not given, then the direction of maximum radiation is implied.
Gain	The gain of an antenna is the ability to convert the input power into radio waves in a particular direction. Gain is the combination of the directivity and the electrical efficiency of the antenna. Electrical efficiency of an antenna takes into account the matching between the feed line and antenna as well as internal losses in the antenna. Hence, gain is always less than the directivity because most of the antennas have some internal losses. The antenna gain is often given as dB relative to an isotropic antenna, and abbreviated dBi.
e.i.r.p.	e.i.r.p. is the total power that would have to be radiated by an isotropic antenna to give the same radiation intensity (signal strength or power flux density) as the actual source antenna at a distant receiver located in any given direction. Its value is the transmitter power (in logarithmic units) plus the antenna gain in dBi.
TRP	TRP is defined as the integral of the power radiated by an antenna array system in different directions over the entire radiation sphere. TRP is equal to the total conducted power input into the antenna array system less any losses in the antenna array system.

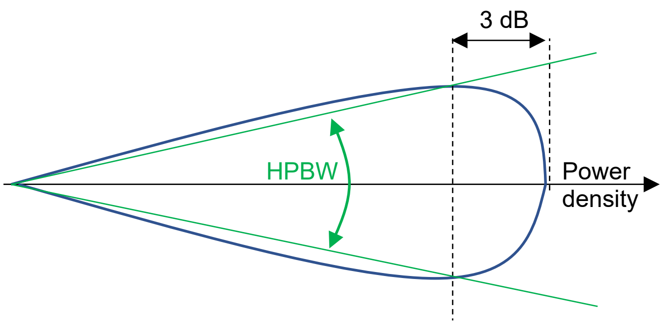
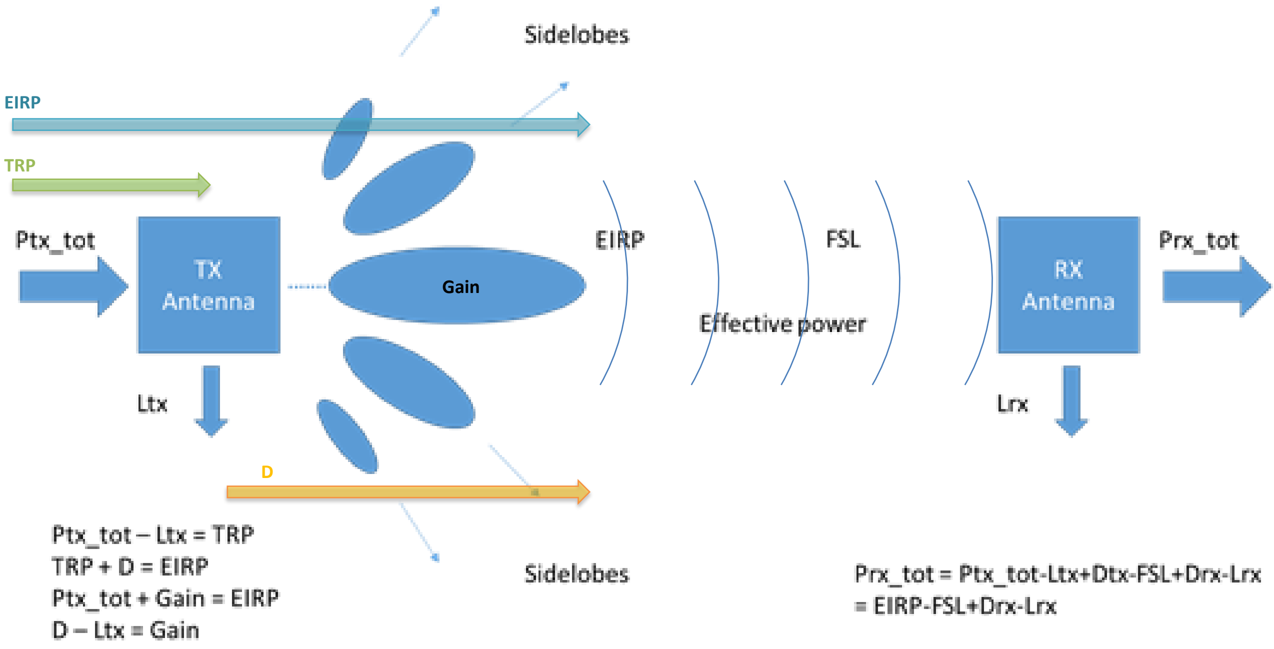


Figure 1: Visual representation of half-power beamwidth (HPBW)



* Ptx_tot – Total transmitted power, Prx_tot – Total received power, Ltx – Transmitting antenna losses, Lrx – Receiving antenna losses, D – Directivity, Dtx – Transmitting antenna directivity, Drx – Receiving antenna directivity, FSL – Free Space Loss

Figure 2: Illustration of directivity, e.i.r.p. and TRP

3 OUTLINE OF FRAMEWORK AND REQUIREMENTS OF MEASURING 5G AAS IN THE FIELD

3.1 5G AAS IN EUROPEAN REGULATION

Some examples of ECC and EC Decisions where AAS requirements have been added in terms of TRP are as follows:

Table 1: Examples of ECC and EC Decisions which include TRP requirements for AAS

ECC Deliverable	Corresponding EC deliverable	Frequency band	Date TRP requirements included for AAS
ECC Decision (05)05 [1]	Decision (EU) 2020/636 [2]	2500-2690 MHz	July 2019
ECC Decision (06)01 [3]	Decision (EU) 2020/667 [4]	1920-1980 MHz and 2110-2170 MHz	March 2019
ECC Decision (11)06 [5]	Decision (EU) 2019/235 [6]	3400-3800 MHz	October 2018
ECC Decision (18)06 [7]	Decision (EU) 2020/590 [8]	24.25-27.5 GHz	October 2018
ECC Decision (06)13 [18]	Decision (EU) 2022/173 [19]	1710-1785/1805-1880 MHz	March 2022

In addition, in ERC Recommendation 74-01, “Unwanted emissions in the spurious domain” (amended May 2019), [9] TRP is defined as the metric for unwanted emission for terminals and base stations using AAS and beamforming with integrated antennas (see Annex 2, Table 6, Note 6). It should be noted that some of the above-mentioned deliverables refer to unwanted emissions while this Report focuses on in-band.

3.2 SCOPE AND LIMITATIONS OF MEASUREMENTS IN THE FIELD

Administrations need to measure emissions from transmitters for various reasons. This includes the need to measure emissions from 5G base stations using active antenna systems (AAS). For obvious reasons, it is not possible to measure a transmitter deployed in the field in a controlled environment. Furthermore, 5G base stations using AAS usually do not provide a test point allowing conducted measurements. Therefore, all measurements have to be performed as radiated measurements in the field.

In the field, radiated measurements can only measure the field strength at the measurement location. All methods described in Section 4 are based on this principle. This process is already subject to influences from propagation and reflections. Additional uncertainties are introduced for those methods aiming to determine the e.i.r.p. and TRP, because they include additional calculation processes that often depend on certain assumptions and may even be dependent on the availability of certain information from external sources (e.g. antenna characteristics, beam directions).

For the above reasons, field measurements cannot be expected to provide the same accuracy and reproducibility than measurements in a controlled environment as assumed by the 3GPP specifications and ETSI standards. The measurement methods described in Section 4 for the different purposes are associated with uncertainties that have to be considered carefully before making conclusions about the compliance or non-compliance with the applicable limits especially for airborne measurements (further information could be found in ITU-R Report SM.2056 [15]). Often the more complex methods result in more accurate results whereas in some cases the accuracy of the simpler method may be sufficient. The desired accuracy of the result should be an important criterion when selecting a method for a specific measurement task.

The following sub-sections describe the main situations in which measurements of 5G AAS base stations are necessary.

3.2.1 Verification of licence conditions for 5G AAS base stations

The conditions of a licence to operate a base station generally include limits on the transmitter power and also require compliance with the relevant harmonised standard based on 3GPP specifications. 3GPP specifications contain limits for the unwanted emissions in both OoB and spurious domain. Limits for the transmitter power are either defined as e.i.r.p. or as TRP for AAS, while limits for the unwanted emissions are generally defined as TRP for AAS.

As mentioned earlier, this Report is limited to in-band measurements.

3.2.2 Interference investigation

A 5G AAS base station can cause harmful interference in two ways:

- due to on-channel RF level; or
- due to unwanted emissions that fall inside the receive channel of the victim receiver.

As mentioned earlier, this Report is limited to in-band measurements, which would apply to the first case. The general procedure is to measure the field strength of the 5G AAS base station at the location of the interfered receiver. This value may then be compared with the requirements of the receiver regarding resilience/selectivity, or calculated back to e.i.r.p. or TRP for comparison with the assigned power of the 5G AAS station.

3.2.3 Other measurement scenarios

Since base stations for public mobile networks are also placed near borders, coordination with networks in neighbouring countries is required. In this process, the maximum field strength either directly at the border or a certain distance away from the border is negotiated. Measurements may have to be performed to check compliance with bilateral or multilateral agreements.

There are also other scenarios in relation to measuring emissions from 5G AAS in the field, including coverage and EMF measurements. However these measurements are outside the scope of this Report.

4 MEASUREMENTS, REQUIREMENTS AND METHODS

4.1 DETERMINATION OF TRP

In CEPT Report 67 [10], TRP is defined as the integral of the power radiated by an antenna array system in different directions over the entire radiation sphere:

$$TRP = \frac{1}{4\pi}\int_{0}^{2\pi}\int_{0}^{\pi} P(\theta,\varphi)\sin(\theta)\,d\theta d\varphi \qquad (1)$$

Where:

- θ: elevation angle in radians
- φ: azimuth angle in radians
- P(θ,φ): Power radiated by an antenna array system in the direction (θ,φ).

An example of P(θ,φ) is shown in Figure 3.

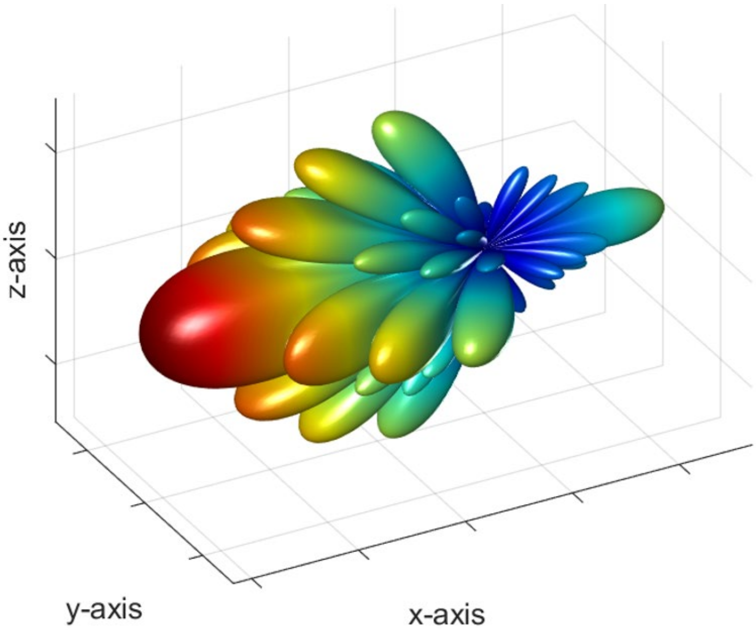


Figure 3: 3D polar plot of an 8x8 antenna array radiation pattern

The TRP is also equal to the transmitter power supplied to the antenna minus any losses. Its value cannot be measured directly. In practice, the field strength *E* at a certain location (or multiple locations) is measured, from which the TRP may be calculated under certain conditions (see section 4.4.3 for details).

4.2 KEY FUNCTIONALITY OF 5G NR AAS BASE STATIONS

5G NR (a specific radio access technology of 5G as defined in relevant 3GPP specifications) uses OFDM modulation with flexible RF parameters such as number of subcarriers, symbol duration and bandwidth. Information transmitted from the base station is separated into broadcast, synchronisation and traffic channels.

All data transmission is organised in resource blocks (RB) which are organised by a scheduler.

Synchronisation and broadcast blocks are always transmitted once per frame and occupy only part of the total channel bandwidth. This block consists of up to 240 consecutive subcarriers and is three to four OFDM symbols long.

Resource blocks for user traffic are only switched on when required. The scheduler decides how many RBs are assigned to a user and for how long. They may occupy a smaller portion of the available RBs for a longer time, or the full bandwidth for a shorter time. This results in a highly dynamic spectrum in both time and frequency domain, which heavily depends on user traffic and configuration of the base station.

In addition, a specific issue of AAS is beamforming. This feature allows the creation of dynamic radiation patterns with different beamwidths and beam directions. In 5G NR, broadcast and synchronisation blocks are transmitted via so-called SSB (synchronisation signal block) beams, whereas traffic blocks are transmitted via traffic beams. SSB and traffic beams usually have different beamwidths and spatial coverage ranges.

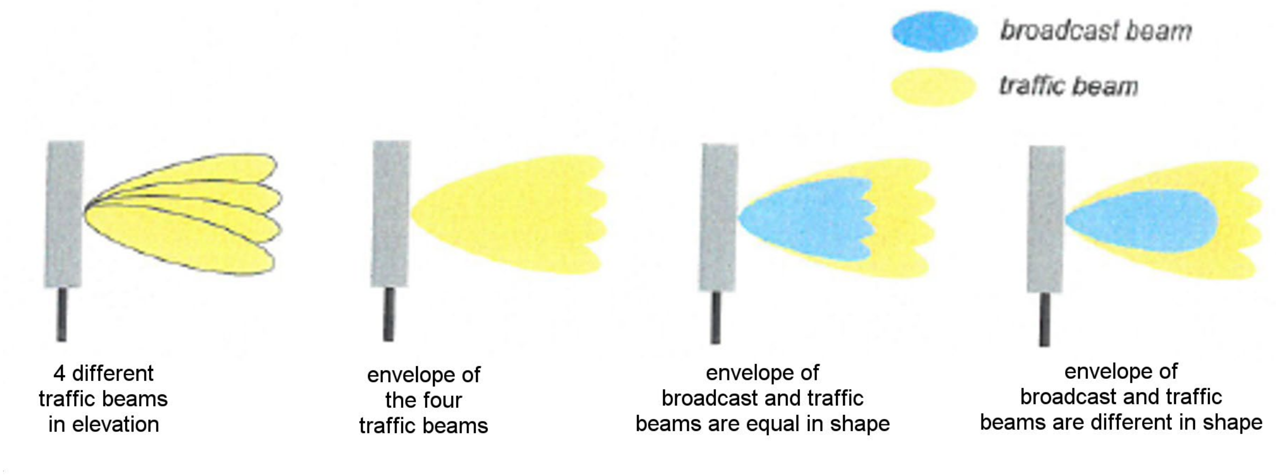


Figure 4: Example of different beam characteristics of a 5G AAS base station

Configuration of the SSB beams is variable. A station may be configured to transmit only one broadcast block per frame over a beam with 120° opening angle, or up to 8 SSB beams transmitted in sequence over narrow beams in different pre-defined and fixed directions. The following figure is an example of a station configured for 7 SSBs, numbered Beam0 to Beam6.

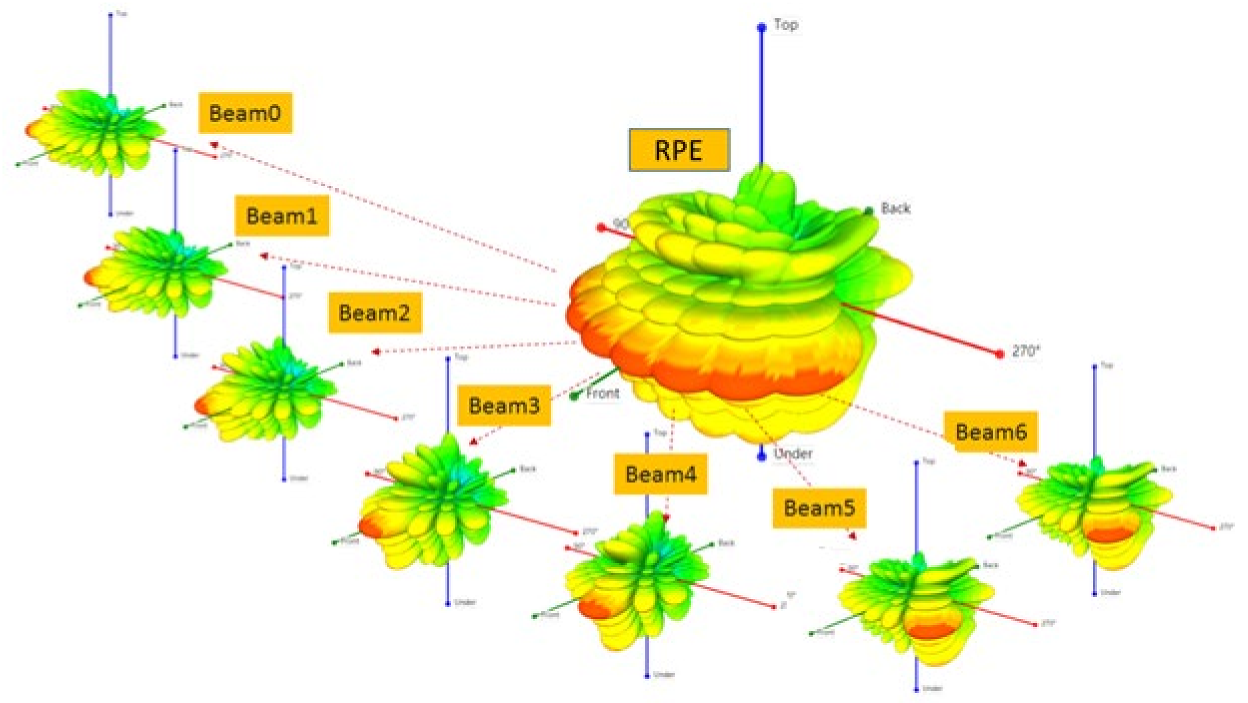


Figure 5: Spatial distribution and patterns of a 5G NR BS with 7 SSB beams

Although all SSBs are transmitted with equal power, a time domain measurement (zero span) of such a BS, taken at a fixed location in the direction of Beam4, may appear as follows:

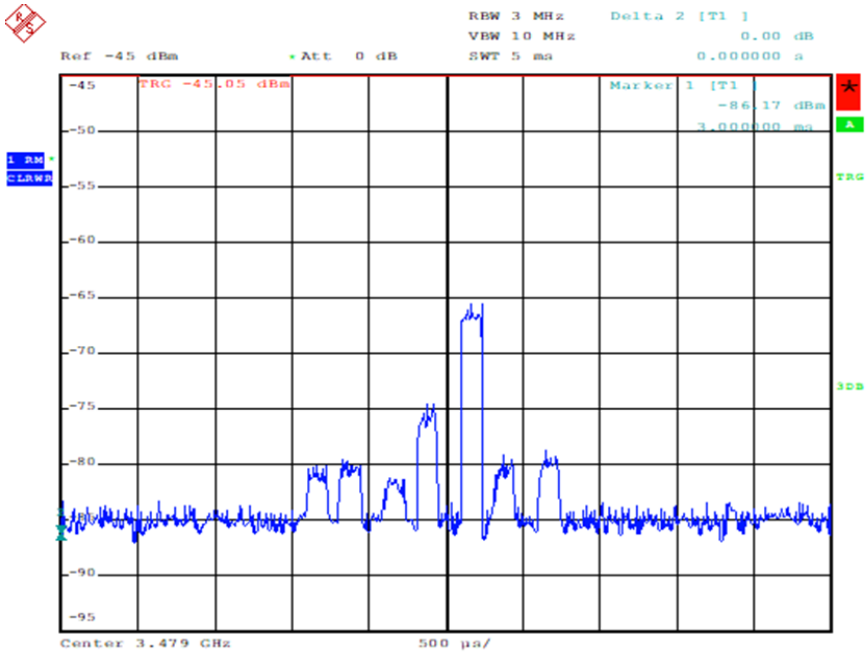


Figure 6: Example of the power vs. time received from the SSBs at a fixed location

Traffic beams of a 5G AAS base stations can be focussed in different directions which makes it possible to “follow” (i.e. select most suitable of pre-defined beams to provide best experience to) a moving user (beam steering). This allows concentration of the available transmit power in a certain direction as necessary. It is even possible to create multiple beams in different directions simultaneously as shown in the following figure.

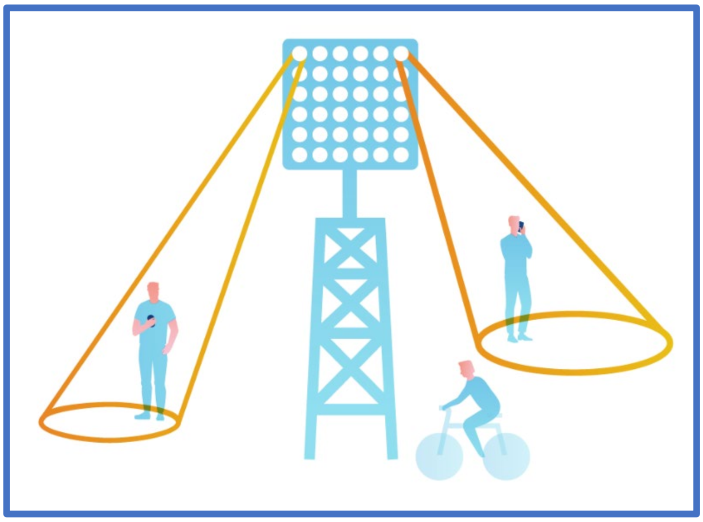


Figure 7: Beam steering

The dynamic spectral and time behaviour of a 5G NR base station and the variable beamwidth and directions of AAS make measurements of maximum field strengths very complex and challenging.

4.3 MEASUREMENT SIGNAL AND BASE STATION REQUIREMENTS

Over-the-air measurements of 5G AAS base stations can principally be based on measurements of the SSB beam and/or traffic beam. Depending on the purpose of the measurement, the available equipment, operation mode of the base station, and local constraints regarding possible measurement locations, the decision for a specific signal/beam to be measured may have different advantages and disadvantages.

Table 2: Measured signals and conditions

Measured signal/beam	Measurement condition
Broadcast signal/SSB	Normal operation
Traffic signal/traffic beam(s)	a) Provoking traffic and attracting a traffic beam b) Test mode of the base station simulating traffic

Since the SSB is always transmitted, it can be measured during normal operation of the base station. In case it is only required to determine the actual signal level (no estimation of maximum possible level), it may even be sufficient to measure the traffic signals during normal operation, possibly over longer averaging times.

If measurement of the traffic signal by attracting a traffic beam (for example with a UE in the direction of the measurement location and downloading data) aims to determine maximum e.i.r.p. or TRP, it may be required that no other users are active during the measurement. If this can be guaranteed, the measurement may also be possible under normal operating conditions of the base station.

The most reliable and reproducible method to determine maximum e.i.r.p. or TRP may be to set the base station into a test mode where maximum power is transmitted in a defined direction. It should be noted that currently there is no requirement for a specific test mode defined in 3GPP. Some vendors of 5G AAS base stations may provide the possibility of test modes, but knowledge of the spectral, time domain and spatial properties of these test signals is required to obtain the required result.

4.4 MEASUREMENT APPROACHES AND PARAMETERS

Depending on the purpose of the measurement, and relevant regulations, the final parameter to be determined may be either field strength, e.i.r.p. or TRP. While the primary value measured directly is the received power or power density, the other values may be calculated under certain conditions. The following table lists required measurement locations, approaches and a-priori information.

Table 3: Measurement modes and required information

Required parameter	Measurement location(s)	Required a-priori information
Field strength	Fixed	None
e.i.r.p.	Fixed (ground-based) or variable (possibly airborne/drone)	a) Antenna gain (if measurement location can be assured to be in the main beam direction) b) Antenna pattern (if measurement location may be outside the main beam direction)
TRP	Variable at least over part of the sphere (possibly airborne/drone)	None

4.4.1 Field strength determination

Primarily, the parameter measured directly is the power at the input of the measurement receiver. Because the normal 5G NR signals are pulsed, the average burst power has to be measured. This is the RMS power only during a burst, excluding pauses.

If the SSB signal is measured with a spectrum analyser or standard measurement receiver, the measurement has to be in the time domain (zero span) and limited in time to the (strongest) burst only. The result is a display as in Figure 6. For spectrum analysers, a specific measurement mode is needed. This is sometimes called “time domain power” or “gated trigger”.

Often the measurement is taken in a bandwidth that is smaller than the signal to be measured. For spectrum analysers, the measurement bandwidth is the RBW used which is generally not sufficient to cover the whole 5G channel, and sometimes even narrower than the SSB. If dedicated 5G measurement equipment is used, the received power is often shown in dBm per resource block. This level corresponds to a measurement bandwidth that is equal to the subcarrier spacing.

From a measurement with reduced bandwidth, the total signal level can be calculated with:

$$P_{signal} = P_{meas} + 10log_{10}\left(\frac{signalBW}{measBW}\right) \quad (2)$$

Where:

- P_{signal}: Total level of the signal;
- P_{meas}: Level measured in measurement bandwidth;
- measBW: Measurement bandwidth;
- signalBW: Signal bandwidth.

Using the antenna factor of the measurement antenna, the corresponding field strength can be calculated from the received level using:

$$E\left[\mathrm{dB\mu}\frac{\mathrm{V}}{\mathrm{m}}\right] = P_{signal}[\mathrm{dBm}] + K[\frac{\mathrm{dBm}}{\mathrm{m}}] \quad (3)$$

Where:

- E: Field strength of the signal at measurement location;
- P_{signal}: Total level of the signal;
- K: Antenna factor of the measurement antenna.

If the maximum possible field strength from the 5G base station is to be determined, and the SSB is measured, it may be estimated by using equation (2), but only under the following conditions:

- The measurement location is in the main lobe of both SSB and traffic beam;
- The e.i.r.p. of SSB resource blocks and traffic resource blocks is assumed to be equal.

While the first assumption may be assured by varying the measurement location, the second assumption requires information from the operator or base station manufacturer. If this information is not available, the traffic beam has to be measured for reliable results.

4.4.2 e.i.r.p. determination

The e.i.r.p. in the direction of the measurement location can be calculated as follows [16]:

$$EIRP[\mathrm{dBW}] = E\left[\mathrm{dB\mu}\frac{\mathrm{V}}{\mathrm{m}}\right] + 20\,log_{10}(r[\mathrm{km}]) - 74.8\ \mathrm{dB} \quad (4)$$

Where:

- r: Distance between transmit antenna and measurement location

Often, the maximum e.i.r.p. is required. For directional antennas, this corresponds to the angle of maximum antenna gain only. However, e.i.r.p. can be calculated for any angle using the formula above.

4.4.3 TRP determination

In this Report, in-band measurements will be discussed. In this case the directivity of the transmit antenna:

$$D(\theta,\phi) = \frac{EIRP(\theta,\phi)}{TRP} \quad (5)$$

is assumed to be known or directly related to the beamwidth of the radiation pattern. The latter form implies:

$$TRP = \frac{EIRP(\theta,\phi)}{D(\theta,\phi)} \quad (6)$$

Typically the direction of peak directivity, and peak e.i.r.p., is used.

The following relation is used to relate directivity to beamwidth [17]:

$$D_{max} = \max[D(\theta,\phi)] = \frac{32400}{HPBW_V HPBW_H} \quad (7)$$

$HPBW_x$ denotes vertical and horizontal half power beamwidth, respectively. Note that these beamwidths should be measured from the coordinate origin which implies a scaling factor if the horizontal beamwidth is measured in a conical cut $\theta = \theta_{cut}$ using angles (ϕ) in the cut, i.e.:

$$HPBW_H = \sin\theta_{cut}\, HPBW_\phi \quad (8)$$

Here, θ_{cut} is the theta angle at which the horizontal conical cut is taken. Note also that the validity of Eq. (7) is based on a pattern that has only one major lobe. Any minor lobes, if present, should be of very low intensity.

To achieve an absolutely accurate value for the TRP, the whole sphere around the transmit antenna would have to be measured. However, this is normally not possible in practice. 3GPP TS 37.145-2 [11] defines a method to obtain an estimate of the TRP from determined e.i.r.p. values as follows:

$$TRP_{Estimate} = \frac{\pi}{2NM}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} EIRP(\theta_n,\varphi_m)\sin\theta_n \quad (9)$$

Where:

- N: the number of samples in the θ angle;
- M: the number of samples in the φ angle.

Each (θ_n, φ_m) is a measurement sampling point. The sampling angular intervals for θ and φ are $\Delta\theta = \frac{\pi}{N}$ and $\Delta\varphi = \frac{2\pi}{M}$ [11].

Under certain conditions it may be possible to derive a TRP estimate from a measurement at a single location. The measured power density of the test signal can be expressed as follows:

$$P_D = \frac{P_{rx}}{A} \quad (10)$$

or

$$P_D = \frac{P_{rx} 4\pi}{G(\theta_2, \varphi_2)\lambda^2}$$

where P_{rx} is the power measured at the signal analyser input RF port, A is the antenna aperture area and θ_2, φ_2 are the vertical angles from BS antenna to the test point.

The e.i.r.p. of test signal towards a measurement antenna located under a certain vertical and horizontal angle, $EIRP_{test}(\theta_2, \varphi_2)$, can be expressed as:

$$EIRP_{test}(\theta_2, \varphi_2) = 4\pi r^2 P_D = \frac{P_{rx}(4\pi r)^2}{G(\theta_2, \varphi_2)\lambda^2} \quad (11)$$

where r is the distance between BS and measurement antenna and $G(\theta_2, \varphi_2)$ is the measurement antenna gain towards BS. The TRP of test signal equals:

$$TRP_{test} = \frac{EIRP_{test}(\theta_2, \varphi_2)}{D(\theta_1, \varphi_1)} \quad (12)$$

where $D(\theta_1, \varphi_1)$ is the directivity in the direction towards the measurement antenna. This information has to be provided by the BS manufacturer. The carrier TRP is then calculated as:

$$TRP = TRP_{test} * C \quad (13)$$

where C is a scaling factor to account for the power ratio of test signal to full carrier signal. This information also has to be provided by the BS manufacturer. The locations and orientations of both BS and measurement antenna are required to determine r, θ_1, φ_1, θ_2 and φ_2.

4.5 SELECTION OF MEASUREMENT METHOD

As mentioned in section 3.2, administrations need to perform over-the-air measurements of radio devices such as mobile base stations deployed in the field for a variety of reasons. There is no single solution for all AAS field measurement scenarios and there could be a range of options. The actual “measurement method” is a combination of the requirements, conditions and available equipment as elaborated in sections 3.2, 4.3 and 4.4. Among others, the choice of applicable approach/method may depend on the following:

Purpose and result of measurement:

- Is it only necessary to measure the field strength at a predetermined location (e.g. at the point of interference, or at the border), or is the maximum possible radiation (e.i.r.p./TRP) from a base station to be determined (e.g. for checks for licence compliance)?

Status of the base station:

- Can the base station be put into a test mode, or does the measurement need to be performed under normal operating conditions?

Constraints from the location:

- Does the area around the base station allow free selection of measurement points, or is it dominated by obstructions?
- Can a reflection-free environment be assumed?
- Can it be assured that the measurement location(s) are in the main lobe of the transmitted beam(s)?

Available equipment:

- Is an air-based measurement (e. g. with a drone) available, or does the measurement need to be performed on the ground?
- Is it possible to attract a traffic beam with a (modified) UE?
- Is a dedicated 5G measurement receiver available that can decode the signal and measure single resource elements, or is the measurement planned to be performed with general monitoring equipment such as a spectrum analyser?

Another important aspect that influences the selected method is the available and required measurement uncertainty. It should be noted that there are many uncertainties in the measurement, some of them common to OTA measurements in controlled environments (see for reference 3GPP TR 37.941 Annex A [13]) and some specific to outdoor environments.

These uncertainties result from:

- Pointing misalignment between the AAS BS and the receiving antenna;
- Mutual coupling between the AAS BS and the receiving antenna;
- Multi-path between the AAS BS and the receiving antenna;
- Environmental interference;
- Polarisation mismatch between the AAS BS and the receiving antenna;
- Phase curvature due to limited far-field conditions;
- Distance measurement deviation between the AAS and the receiving antenna;
- Atmospheric attenuation;
- Uncertainty of the absolute gain of the reference antenna;
- Influence of the receiving antenna feed cable;
- Uncertainty of the RF power measurement equipment (e. g. spectrum analyser);
- Temperature effects;
- Impedance mismatch between the receiving antenna and RF cable;
- Impedance mismatch between the RF cable and measurement equipment;
- Random uncertainty.

The magnitude of these factors also depends on the operating frequency band.

Additional uncertainties are related to the measurement approach and calculation of e.i.r.p./TRP from the measured values. For example, when measurements at multiple locations are combined to estimate TRP, the degree of confidence will generally improve with a higher density of the angular sampling around the BS [12] [13].

Additional uncertainties for drone measurements are related to precision of drone GNSS positions (longitude and latitude) and altitude.

5 MEASUREMENT EXAMPLES

This section contains case studies (including simulations) of actual 5G measurements based on selected methods.

5.1 IN-FIELD GROUND-BASED MEASUREMENT OF THE SSB

5.1.1 Description

Instead of taking a large number of e.i.r.p. measurements, this example focuses on determination of e.i.r.p. at a single point which is then used to extrapolate to full carrier power or to convert an equivalent or a proxy for TRP in the field.

To convert an e.i.r.p. test/reference sample to TRP, the following information is necessary:

- BS antenna orientation and location;
- In case of measuring reference signal, the carrier resource element power allocation profile is required to extrapolate full carrier power;
- Measurement equipment antenna gain and orientation towards BS.

For this measurement, the main lobe of an SSB beam is used for the position of the test point.

5.1.2 Measurement procedure

The Synchronisation Signal Block (SSB) signal is taken into consideration in order to convert the measured received power to the TRP value. Since the SSB signal is always present independently from the specific traffic pattern, measuring TRP from SSB does not affect traffic and does not require a specific test mode or test signal.

The 5G outdoor base station is located in Shanghai.

The relevant station data is as follows:

- AAU type: AAU 5613;
- Centre frequency: 3750 MHz;
- Duplex mode: TDD;
- NR frequency band: 3GPP n78;
- Configured TRP: 53 dBm;
- Bandwidth: 100 MHz (273 Resource Blocks, RBs);
- Antenna gain: 25 dBi (main beam);
- SSB Beam: vertical down-tilt 6°, Horizontal angle range 105°;
- Downlink/uplink ratio: 4:1;
- Height: 30 m;
- Location: longitude 121°37.4226′, latitude 31°15.5911′;
- Antenna azimuth direction: 0°;
- Antenna down-tilt (Mechanical): 20°;
- Antenna polarisation: +- 45°.

Figure 8: 5G NR base station

The key points of the SSB TRP measurement solution are as follows:

- Accurate measurement of SSB TDD signals;
- Accurate calculation of SSB beam gain and transmission insertion loss.

There is no TDD trigger signal in the field, so the SSB signal measurement is performed in demodulation mode. The R&S-TSMA6-scanner has an SSB signal demodulation function. Alternatively, a spectrum analyser could be used at zero span and locked to the known duration of the SSB, but it would be difficult to separate the SSB signal from the signal spectrum in normal operating conditions due to traffic.

The selection of the receiving location is the key to accurately calculate the SSB beam gain; in particular:

- far-field conditions are necessary;
- the test Rx antenna should be sufficiently high to minimise the effect of ground reflections;
- multipath reflections should be minimised, also by repeating the measurement at different locations in the sector.

For the beam pattern, the energy curve within the 3 dB beamwidth of the main lobe is smooth; therefore, the accuracy of beam gain calculation is optimal when the test point is selected in the main lobe area.

The SSB beam direction area on the map can be obtained based on the known base station location and SSB beam information, as shown in Figure 9. The main beam direction area is selected as the receive position in this test.

According to the beam sweeping behaviour of SSB, the beam carrying SSB information is periodically swept in space in some specific directions, 7 in this case. The radiated pattern envelope (RPE) looks like the one in the centre of Figure 5.

Since the measurement is performed on the e.i.r.p. of one SSB beam, the sidelobe energy of the beam does not affect the test result.

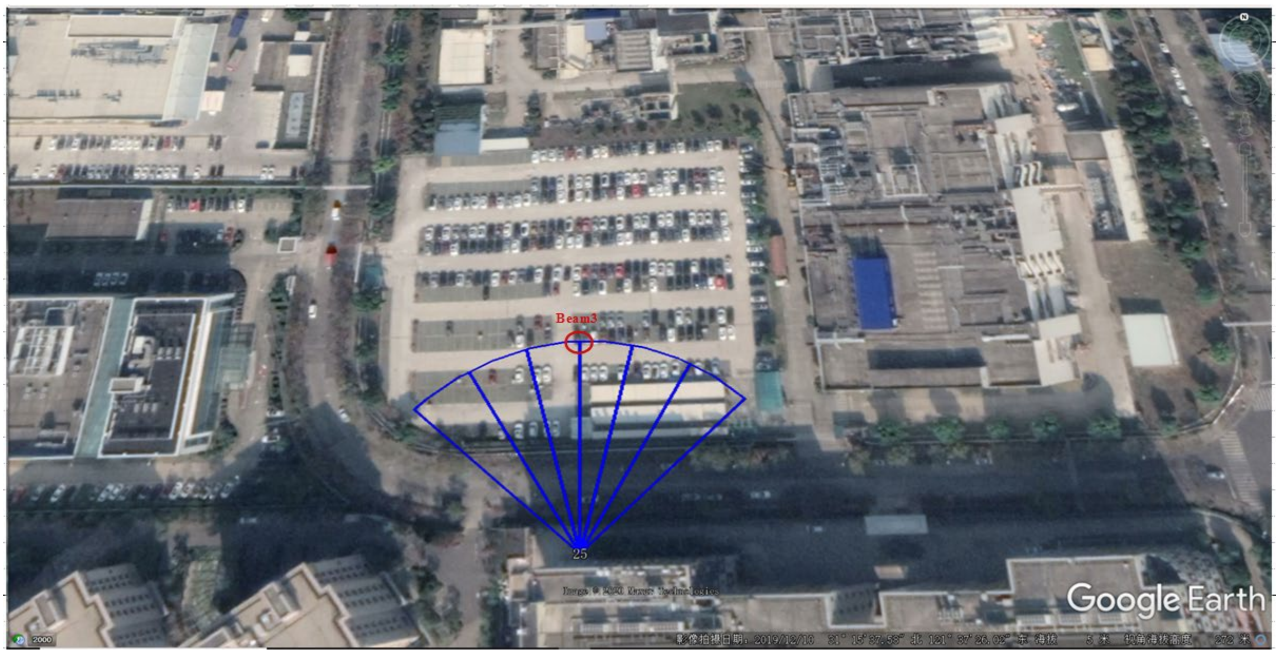


Figure 9: SSB beam direction on the map

The relevant data of the measurement position are:

- Receiving instrument：R&S-TSMA6
- Rx antenna： the gain of the standard horn antenna is 12 dB@3750 MHz, including a 2 m RF cable
- Receiving location: longitude 121°37.25′25.35″, latitude 31°15′37.43″, 60 m away from the base station
- Rx antenna is vertically polarised

In order to align the SSB beam in the receiving location azimuth and elevation; polarisation of the Rx antenna and the position in the 3 dB beamwidth area are to be adjusted until the receiving instrument receives the maximum power.

The measurement results and calculation process are as follows:

$$TRP(dBm) = P_{RxSSB}(dBm) + IL(dB) - G_{Rx}(dBi) + FSL(dB) - G_{Tx}(dBi) + 10\log(N_{subcarrier} * N_{RB})(dB) \quad (14)$$

Where:

- P_{RxSSB}: received RE power of one SSB beam = -27.1 dBm for SSB index 3;
- *IL*: Rx cable insertion loss = 1 dB;
- G_{Rx}: Rx antenna gain = 13 dBi;
- *FSL* = Free Space Loss = 80.5 dB over a distance of R=√30^2+60^2=67.08 m;
- G_{Tx}: Tx antenna gain = 25 dBi;
- $N_{subcarrier}$: number of subcarriers = 12;
- N_{RB}: number of resource blocks in 100 MHz = 273.

The measured TRP is equal to -27.1 dBm +1 dB -13 dBi +80.5 dB -25 dBi +10*log (12*273) = 51.5 dBm

As the configured TRP is 53 dBm, the deviation between the measured TRP and the configured TRP is 1.5 dB.

The power of one SSB beam used for RSRP (Reference Signal Received Power) is the received power of 1 RE, determined as the average of power levels received across all Reference Signal symbols, within the considered measurement frequency bandwidth.

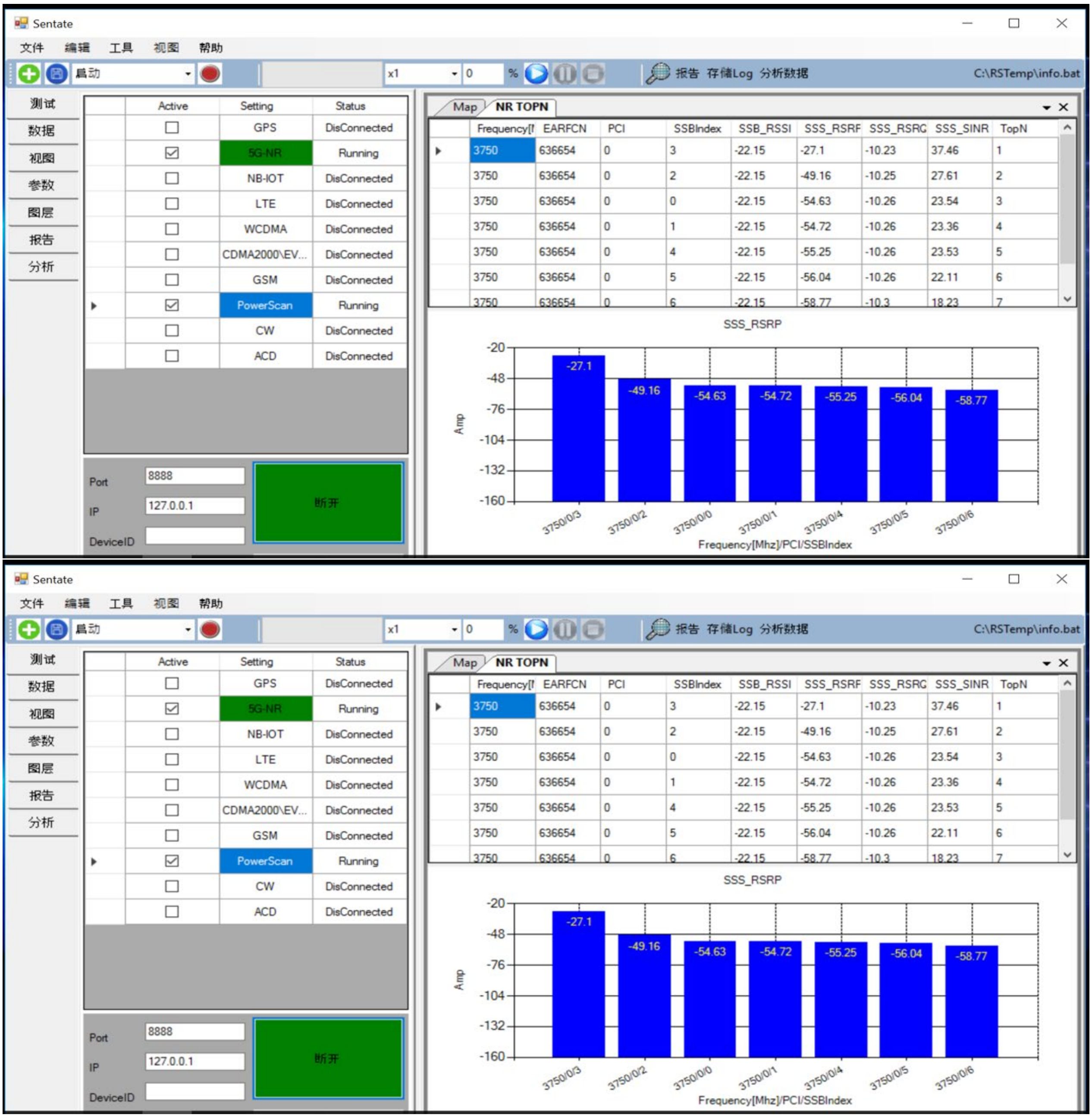


Figure 10: SSB main beam field test result

Notes on the measurement uncertainty:

- The GNSS device is required for selecting the receiving position. The GNSS position precision deviation causes deviation in SSB beam estimation gain. In actual measurement, the distance calculated based on the position precision of the GNSS provided by the R&S scanner causes the measurement result to fluctuate by 1 dB to 2 dB. A GNSS device with higher precision (<1 m) is required to improve the measurement precision;
- Multi-path interference in the field may cause the measurement result to fluctuate by several dB;
- Downlink interference from stations other than the one being measured can result in inaccurate measurements of the wanted station.

The verification result shows that the measurement error is within an acceptable range, which proves the feasibility of the measurement solution.

The measurement uncertainties should be taken into consideration when reviewing the measurement results. These measurement uncertainties have different statistical distributions, but according to the test experience the maximum value of total measurement uncertainty is around 4 dB.

It is assumed that all nearby equipment is time synchronised so that there is no uplink interference.

5.2 AIRBORNE MEASUREMENTS OF SSB AND TRAFFIC BEAMS ON BS IN A TEST MODE

5.2.1 Description

This case describes measurement of both SSB and traffic beams with a drone.

For measurement of the traffic beams, the base station was set into a test mode with an artificial load of 100%. Access to the BS control system was required in order to activate the artificial load.

The levels for the SSB beams can be obtained from the results at the same time. This corresponds to a scenario without specific test mode and can also be performed without artificial load.

5.2.2 Measurement procedure

For measurements of the traffic beam the base station (BS) needs to generate a stable signal during measurement. Specialised equipment (drones) and personnel are required to carry out the measurement.

The SSB beams can be measured to allow extrapolation to full carrier power or conversion to a proxy for TRP in the field without specific test mode.

The 5G outdoor base station is located next to the Nokia campus in Oulu, Finland. The relevant base station and commissioning data is as follows:

- BS type: Nokia 5G BS;
- Centre frequency: 3541.44 MHz;
- Duplex mode: TDD;
- NR frequency band: 3GPP n78;
- Configured TRP: 53.5 dBm;
- Datasheet maximum average e.i.r.p.: 79 dBm;
- NR Bandwidth: 60 MHz;
- Antenna directivity: 24 dBi;
- Beamset vertical downtilt: 6 degrees, Horizontal angle range 120 deg;
- NR SSB Beamset #6, Beams 0-5;
- NR Refinement beams: OFF;
- Antenna height: 33 m.

Figure 11: 5G NR base station

The main purpose of this measurement case is to evaluate drone measurements with a Logger/Scanner NR SSB-logging and R&S Time Gated Spectrum-logging capability for evaluating SSBs and BS TRP while the BS artificial load is set to 100% power.

Figure 12: Flight route 360 degrees around base station tower

The flying route was 360 degrees around the base station tower during artificial load data transfer as shown in Figure 12.

Measurement setup:

- Drone Mission Planner automatic 360 degree flying route;
- Altitude: 29 m (Middle of the beams in elevation perspective);
- Radius: 60 m;

- Groundspeed: 1.5 m/s;
- Logger measuring antenna was horizontally balanced with gimbal and orientation was towards the radio for the whole flight.

R&S Logger measurement probe pattern gain was pre-tested in laboratory:

- Cable Loss: 1 dB @ 3.6 GHz;
- Antenna Gain: 1.5 dBi @ 3.540 GHz.

Note: A wide frequency band measurement probe working equally for both +/-45 deg was selected for this measurement purpose, and its radiation pattern of +45 deg and -45 deg polarisation has been measured when it was installed to the drone, as it was used during the test flights.

R&S logger parameters:

- Time gated spectrum measurement bandwidth: 9.6 MHz “Hunting view”;
- The logger measured 20 kHz frequency steps from 3552 MHz to 3564 MHz, so each sweep contains 950 measurements and overall, 2200 rows of data;
- The logger captured a part of the spectrum that is wider than the bandwidth of the SSB. Pure payload signals from the traffic beams are found outside the SSB frequency block.

The maximum beam peak was searched in the elevation domain. The maximum SSB beam level was defined by flying vertically at the fixed selected distance of 60 m in front of the BS antenna sector to achieve maximum accuracy of the following horizontal direction 360 degree flights in the middle of the beam height. In this case optimum altitude for the horizontal flights was 29 m which is in line with the beamset downtilt of 6 degrees. The 60 m distance was selected due to the fact that the tested BS signal was well above any neighbouring BS or close by UE interference, but still not too close to the BS to ensure that the test was done under far-field conditions.

The next step is to define Time Gated Spectrum and SSB RSRP offset of the SSB frequency block. This measurement is to determine the offset of the dBm reading of the time gated spectrum view to the known calibrated NR SSB RSRP readings of the same device. In later phases this correction is used to compute time gated spectrum amplitude information correctly for the TRP calculations. NR SSB RSRP readings of the test equipment are calibrated information in dBm scale. For this test case, the TRP calculations offset to use the time gated spectrum results is 20 dB.

NOTE: In addition to above correction offset an external 20 dB attenuator is used at the measurement antenna probe port. This 20 dB factor is used in both NR SSB RSRP and time gated spectrum calculations.

According to the beam sweeping behaviour of SSB, the beam carrying SSB information is periodically swept in space in specific directions, which is #6 in this case. Figure 13 shows the measured SSB beams 0-5 in NR SSB Beamset #6 on a radar chart.

Measuring SSB beams was used as a sanity check to verify the beam shape and to ensure that flight altitude was in the middle of the beam. It is also possible to evaluate the expected TRP result mathematically if it is not possible to use artificial load.

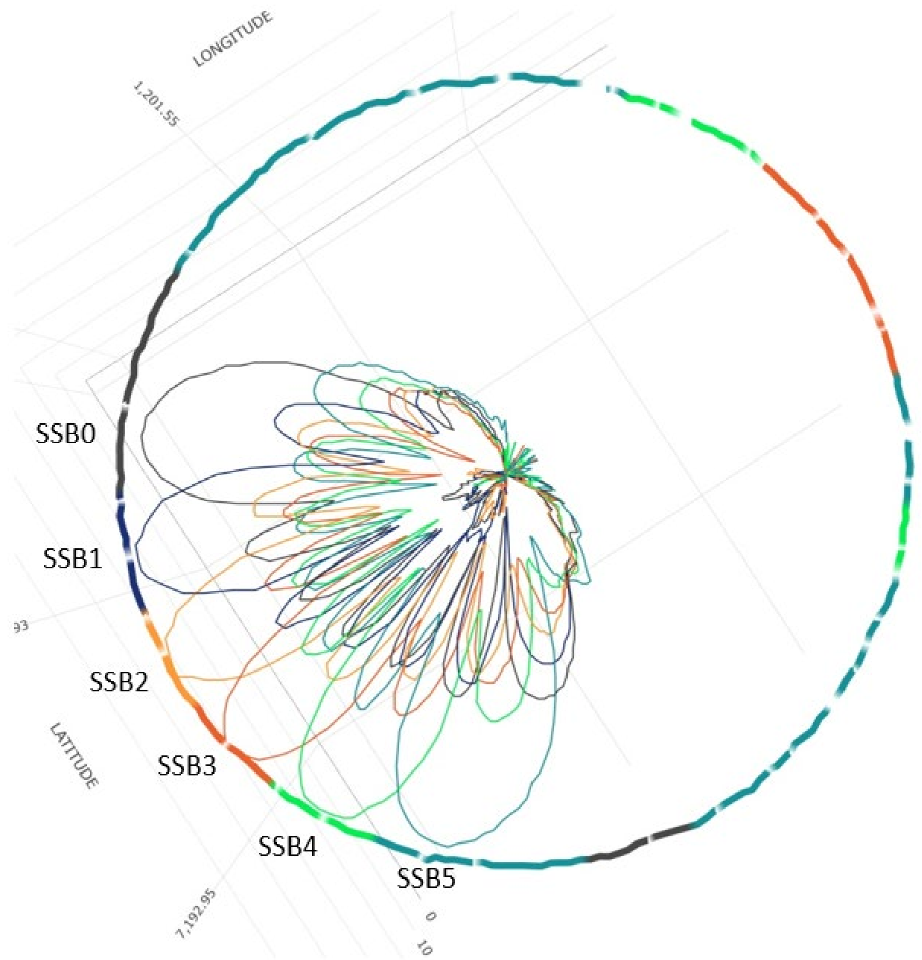


Figure 13: **Used GridOfBeams Beamset #6 Radar Chart (360 deg drone flight)**

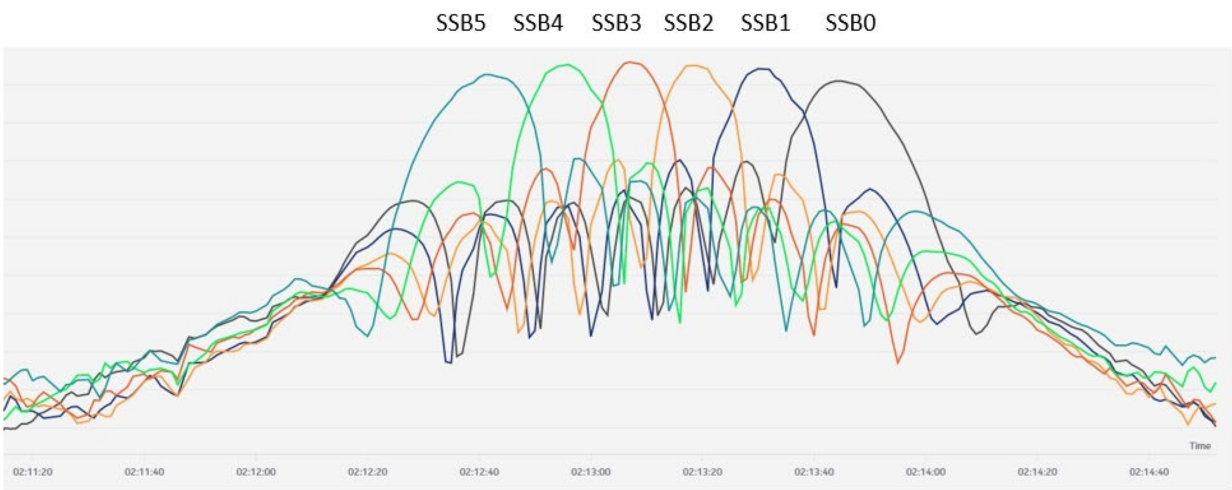


Figure 14: Used GridOfBeams Beamset #6 Horizontal Cut (360 deg drone flight)

Figure 14 shows the measured SSB beams 0-5 in NR SSB Beamset #6 in a horizontal cut of the drone flight. As a reference comparison, the same product was measured in a CATR chamber. Figure 15 shows measured SSB Beamset #6 horizontal cut in a CATR chamber. e.i.r.p. results are normalised, and radiation patters measured by using 3GPP test models. It can be seen that the 360 degree drone flight results match well with the measurement in the CATR chamber.

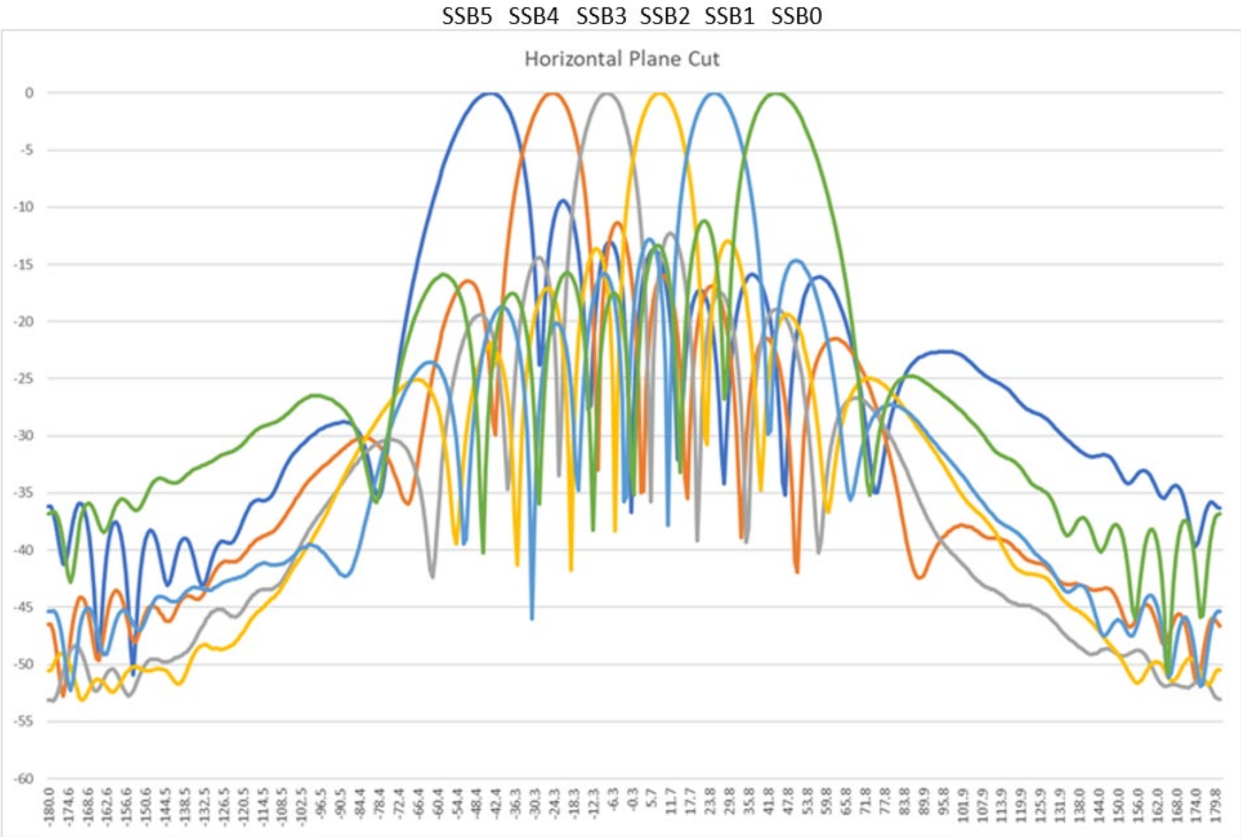


Figure 15: Used GridOfBeams Beamset #6 Horizontal Cut (CATR chamber)

In the CATR chamber the measured average e.i.r.p. is 79 dBm. Calculating TRP from e.i.r.p. results with 24 dBi antenna directivity leads to TRP = 55 dBm with the 3GPP test model.

In the 360 degree drone flight the BS RF power was measured with artificial load set to 100%. Results can be obtained in Figure 16 and Figure 17.

First the correct beam height was measured. This was done by performing an automatic vertical cut in the middle of one beam in the Grid of Beams. Vertical cut height depends on elevation of the environment, antenna tilt and antenna height. In this case the drone was lifted to 80 m and then descended back to 20 m with a speed of 1.5m/s. In the vertical cut visualisation results one can determine vertical beam shape and highest RSRP value for the GNSS altitude of the measured beam. This value gives altitude for 360 degree automatic flight. When the 360 degree automatic flight mission is completed, flight results can be visualised as RF power graphs as in Figure 16 and Figure 17.

To find pure payload, the logger measured the power outside SSB frequency in every measurement point and the results were summed together. This TRP is measured as the envelope of all directions continuously. SSB power and data traffic power are transmitted separately. SSB power is split between used SSB beams. Artificial load sets the data traffic to all SSB beams simultaneously. According to the beam sweeping behaviour of the SSB, the beam carrying SSB information is periodically swept in space in some specific directions, which is 6 in this case.

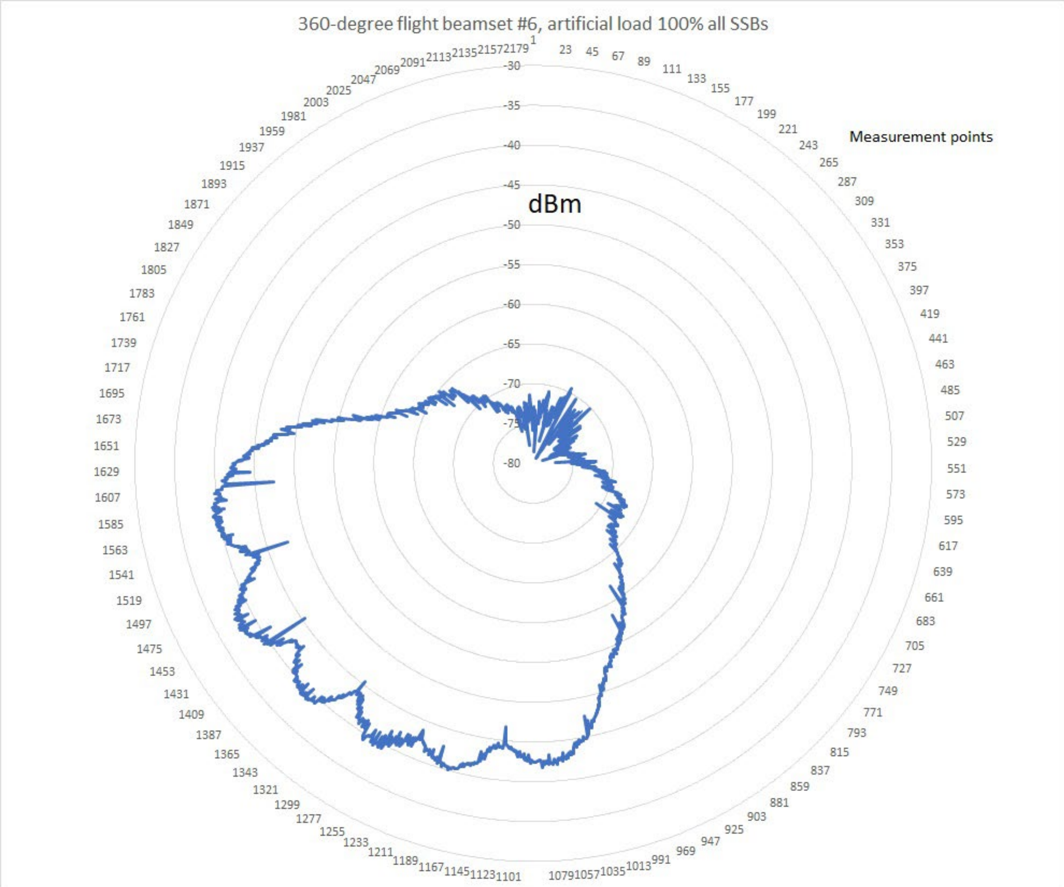


Figure 16: Non-scaled logger RF Power raw result radar chart

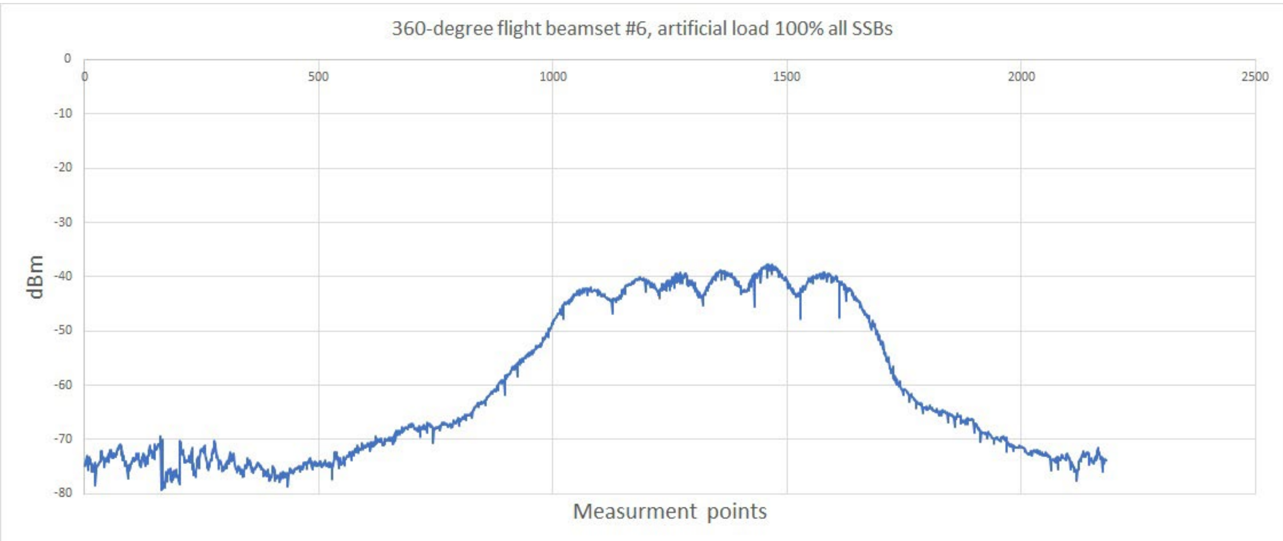


Figure 17: Non scaled logger RF power raw result line chart

Summing of R&S Logger 360 degree route at beam elevation 29 m altitude at 60 m radius:

- Sum of RF power 2200 samples dBm is converted to power (W) and then average power is calculated for the whole 360 degree flight;
- Calculated power (W) is converted to dBm scale and that value is used for TRP calculations: -66.3 dBm;
- 60m distance path loss at 3.541GHz: 79 dB;
- Measuring antenna attenuation: 20 dB;

- Calculated TRP:

  -66.3 dBm + 79 dB (Path Loss) + 20 dB (Time gated spectrum offset) + 20 dB (Measuring antenna attenuator) = 52.7 dBm

  TRP = 52.7 dBm
- Calculated e.i.r.p.:

  52.7 dBm (TRP) + 24 dBi (Antenna directivity gain) = 76.6 dBm

  e.i.r.p. = 76.6 dBm

In the measured radio type datasheet, the maximum average e.i.r.p. was 79 dBm and during the test the configured e.i.r.p. was 77.5 dBm. The measured result is in line with the datasheet considering that vertical part of beam energy is not included on this horizontal flight, so a small part of the overall energy is missing from the result. The error from this measurement can be considered to be in the order of 0.5-1.0 dB.

It should be noted that there are uncertainties in the measurement, which are common when measurements are performed in outdoor environment.

Uncertainties result from:
- Random uncertainty;
- Atmospheric attenuation;
- Outdoor temperature variations;
- RF interference e.g. by external source of BS or UE;
- Uncertainty of the measurement equipment e.g. logger-specific uncertainty;
- Environmental interference e.g. resulting from reflections (e.g. rooftops or other strong reflective surfaces) close to BS;
- Measurement antenna probe e.g. polarity balance and frequency flatness;
- Position and elevation accuracy and stability of the drone e.g. use of reference GNSS and wind effects;
- Measurement probe alignment accuracy towards BS during flight e.g. drone & control software quality;
- Impedance mismatch between RF cable and measurement equipment;
- Geometry-based polarisation mismatch;

It is assumed that all nearby equipment is time synchronised so that there is no uplink interference.

These measurement uncertainties have different statistical distributions, but according to the test experience the maximum value of total measurement uncertainty is around 2-4 dB. It should be noted that the measurement uncertainty is also dependent on the operating frequency band.

This method requires access to the BS control system for activating a test mode in downlink transmission for all the SSB beams with an artificial 100% load. In this measurement case, one sector of the BS is used for the test, but equally all BS sectors could be used simultaneously. In practice the one sector test is better for identifying the beam directions and beam shape more clearly. The method requires a high quality drone and a logger control system to minimise the variation in measurement results. Permission to use a drone and the possibility to fly close to the BS site is also required. This will be challenging in certain geographical locations such as busy urban areas.

This measurement case provides a first proof-of-concept results for drone measurements. The results look quite promising, but more measurements are required to estimate the overall measurement accuracy, variance, and test uncertainties.

The method can also be used for measuring a TRP equivalent from peak beam or from reference beam. While limiting measurements to the SSB, there is no need to access BS control system because SSB beams can be measured without artificial load. In this case the absolute total TRP needs to be calculated from the known alternative simultaneous possible beam directions of the BS.

5.3 IN-FIELD GROUND-BASED MEASUREMENT BY ATTRACTING A TRAFFIC BEAM WITH A TEST UE

5.3.1 Description

This example determines the e.i.r.p. of a traffic signal at different ground-based locations while a UE is used to attract a beam. Three different approaches of the same principle are tested:

- Co-located UE and test antenna;
- Test-UE placed at a fixed location and moving the measurement antenna around this location;
- Measurement antenna at a fixed location while moving the test-UE around.

The TRP is then calculated by integration of the measured power under several angles in the main lobe of the traffic beam. The degree of influence of the angular sampling intervals on the measurement accuracy is also investigated.

The first approach requires knowledge of the directivity of the BS antenna, whereas Method 2 and 3 do not need this information.

The relevant station data is as follows:

- BS type: AIR 5212;
- Centre frequency: 27560 MHz;
- Duplex mode: TDD;
- NR frequency band: n257;
- Configured TRP: 0 dB (relative);
- Bandwidth: 100 MHz;
- Antenna directivity: 23.8 dBi (boresight main beam);
- SSB Beam: not used;
- Downlink/uplink ratio: 3:1;
- Height: 42 m;
- Location: longitude 11.9418, latitude 57.7051;
- Antenna azimuth direction: 13°;
- Antenna down-tilt (Mechanical): 6°;
- Antenna polarisation: V/H;
- Beamforming type: Grid of beams.

It is assumed that all nearby equipment is time synchronised so that there is no uplink interference.

5.3.2 Equipment and system parameters

The test equipment depicted in Figure 18 was used in all measurements. The UE is a 5G device which was used to trigger a traffic beam. A dual-polarised Test Antenna (TA) was mounted on a two axis Elevation (EL) over Azimuth (AZ) positioner. This makes it possible to point the TA in any direction in the upper hemisphere. Each antenna polarisation port was connected to a separate radio receiver unit, each calibrated indoor to a power meter. A GNSS receiver was used to record the position of the TA. The gain of the TA used in the measurement is 38 dBi.

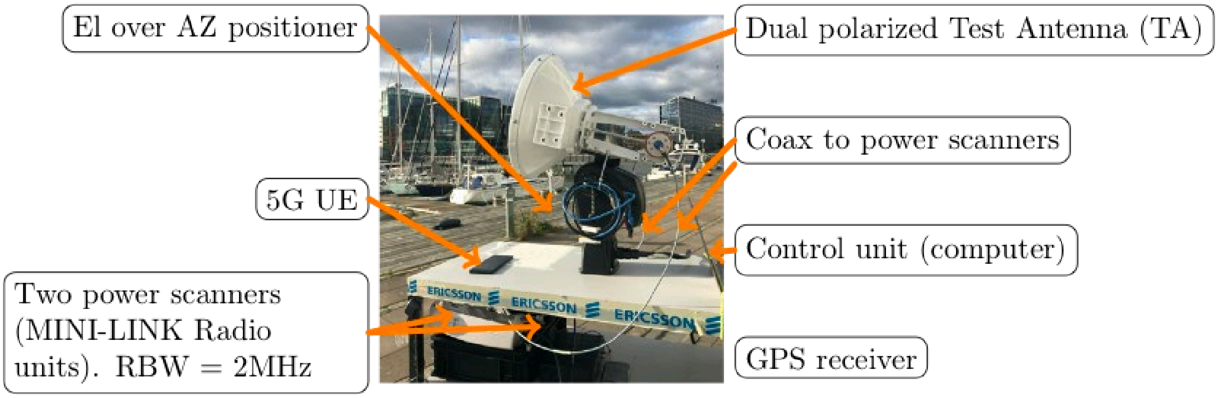


Figure 18:Test Equipment using a 2-axis positioner (scanner) and a high-gain antenna (38 dBi)

A discussion and recommendations on how to select the test antenna is found in ANNEX 1.

5.3.3 Measurement procedures

5.3.3.1 Method 1: Co-located test antenna and UE

In short, this method uses the following principle: Try to direct a beam towards the UE with maximum e.i.r.p., measure power density and scale to TRP using the distance, wavelength and maximum directivity of the AAS.

At each test point the UE is co-located with the TA and the turntable is used to find the direction towards the BS. The TA is directed towards the BS and the received power is measured. Note: due to the fixed grid of beams, the directivity in the measurement direction may be lower than the maximum directivity. Consequently the measured power may be lower that the peak power. The measured power is adjusted for cable losses and related to the power P_{TA} at the TA port. This is then related to the power density by using the effective antenna area A_{TA}:

$$P_D = \frac{P_{TA}}{A_{TA}} = \frac{P_{TA} 4\pi}{G_{TA} \lambda^2} \qquad (15)$$

Here, G_{TA} is the realised gain of the TA. The power density is scaled to e.i.r.p. using:

$$EIRP(\theta, \phi) = 4\pi r^2 P_D(x, y, z) \qquad (16)$$

TRP is then obtained via the directivity (D) of the AAS as:

$$TRP_{est} = \frac{EIRP(\theta, \phi)}{D_{max}} \qquad (17)$$

This will underestimate the true TRP value compared to Eq. (1).

The directivity D_{max} is derived from chamber e.i.r.p. measurements on a boresight beam. In a real situation directivity has to be known.

In a grid of beam design the directivity of the received beam will have a ripple, which will also be present in the estimated TRP. Since the actual directivity is smaller than the peak, this error is one-sided and always gives an underestimation of the TRP value. One crucial part is therefore to try to maximise the e.i.r.p., i.e. move the TA to a point close to the peak direction.

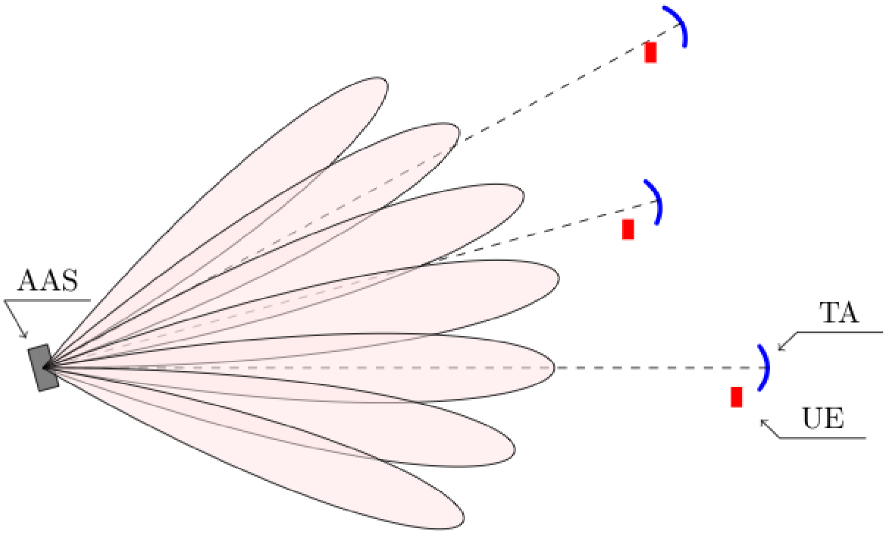


Figure 19: Positions of TA and UE for Method 1

The procedure for this measurement is as follows:

1 Place the test antenna in the service area;
2 Record the GNSS coordinates (longitude, latitude and altitude) of the BS;
3 Start the UE and make sure it triggers a traffic beam towards the TA;
4 Direct the TA towards the BS by maximising the received power as a sum of power over two orthogonal polarisations. Record the GNSS coordinates (longitude, latitude and altitude) of the TA;
5 Convert the received power to e.i.r.p. by first converting the received power to incident power density and then using Eq. (16);
6 Continue to a new test point and repeat steps 4-5 to get an e.i.r.p. value until a maximum e.i.r.p. is found.

Post-processing step

1 Convert the max e.i.r.p. value to TRP by using the directivity of the BS and Eq. (17)

5.3.3.2 Method 2: Moving Test antenna and fixed UE

In the second method the UE is kept at a fixed location, implying that one beam will be selected by the system during the measurement. No other traffic is present in the measurements. The TA is directed towards the AAS from a number of positions. A part of the radiation pattern will in this way be measured in a street level environment. Due to the high gain of the TA (38 dBi), the impact of scattering and RF interference is low. This is an important feature of the measurement setup in order to get a good end result.

The TRP value can now be assessed as a spatial average by using Eq. (18) (see below). An alternative approach is to estimate the directivity from the beamwidth of the measured pattern. Using this information, the directivity can be approximated and used to derive TRP from the e.i.r.p. value obtained by applying Eqs. (15)-(17).

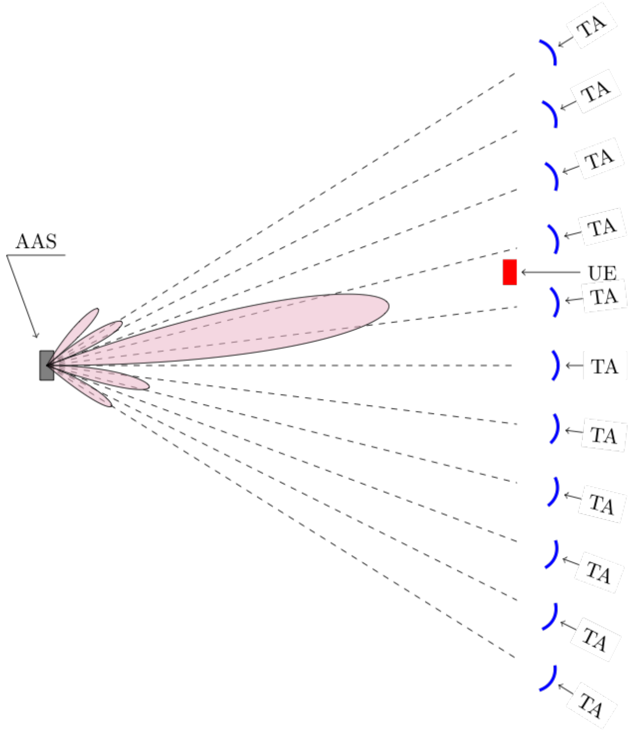


Figure 20: Positions of TA and UE for Method 2

In this method TA (blue, see Figure 20) is used at different locations while the UE (red) is kept at a fixed position. The corresponding e.i.r.p. values from the TA measurements represent a part of the e.i.r.p. pattern. This is used to retrieve TRP.

The procedure for this measurement is as follows:

1 Record the GNSS coordinates (longitude, latitude and altitude) of the BS;
2 Set the UE in the service area of the BS. Try to use a location in the centre of the service area;
3 Start a download process on the UE, (e.g. fast.com) and make sure a high throughput is achieved;
4 Determine a set of test points that cover at least the main beam of the BS. The main beam should now point towards the UE as a consequence of Step 3;
5 At each test point:
   a) Align the TA to reach maximum received power (sum over two orthogonal polarisations);
   b) Record the GNSS coordinates (longitude, latitude and altitude) of the TA;
   c) Make sure the throughput to the UE is maintained.

Post processing steps variant A

6 For each test point:
   a) Scale the received power samples to e.i.r.p. samples, by compensating for cable losses, TA gain and BS-TA distance, see Eq. (16);
   b) Obtain the spherical coordinates of the TA as seen from the BS by using the TA and BS GNSS coordinates respectively;
   c) Calculate the angular distance (great circle distance) to each centre point of the bins of a predefined grid and assign the e.i.r.p. time sample to the angular bin of smallest angular distance.
7 Within each bin (labelled by n), calculate e.i.r.p.$_n$ as the average e.i.r.p. (in linear scale, e.g., using mW or W units) of all e.i.r.p. time samples in the bin.
8 For all bins that lack measured power values, assign zero e.i.r.p.
9 Calculate TRP as a weighted sum of the binned e.i.r.p. values:

$$TRP = \frac{1}{4\pi}\sum_{n} EIRP_n\,\Omega_n \tag{18}$$

Here Ω_n is the solid angle of bin n.

Post processing steps variant B

6 For each test point:
- Scale the received power to e.i.r.p., by compensating for cable losses, TA gain and BS-TA distance, see Eq. (16);
- Obtain the spherical coordinates of the TA as seen from the BS by using the TA and BS GPS-coordinates respectively.

7 Use the derived angular e.i.r.p. pattern from the previous step to estimate the Half-Power Beamwidths HPBWH and HPBWV in the horizontal (H) and vertical (V) directions, respectively. Use the Kraus relation to estimate the peak directivity, i.e. from equation (7),

$$D \approx \frac{180}{HPBWV} \times \frac{180}{HPBWH}$$

8 Find the peak e.i.r.p. by using an adequate interpolation technique.

9 Estimate the TRP as Peak e.i.r.p. from step 8 divided by the estimated Directivity.

5.3.3.3 Method 3: Fixed TA and moving UE

In this method the TA is kept fixed and the UE is moved. As the beam points towards the UE either the main lobe will be sampled (when the UE is close to the TA) or the sidelobe region will be sampled (when the UE is away from the TA).

The GNSS coordinates of the UE is measured versus time. The TA is directed towards the BS and a power trace in time is measured. By synchronising the time scales, the power samples can be related to positions of the UE and further to angles from the BS. To avoid erroneous overweighting of non-independent samples (power samples close in angle to one another) the same binning and integration technique as described for Method 2 is used.

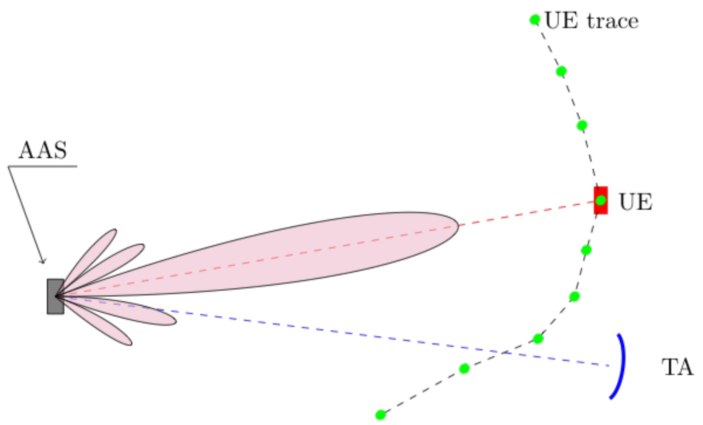


Figure 21: Positions of TA and UE for Method 3

In Method 3 the TA (blue, see Figure 21) is used at a fixed location while the UE (red) is moving. The e.i.r.p. sequence is thus generated by sweeping the beam by directing it towards the moving UE. The e.i.r.p. sample at each time is associated to the direction of the UE as seen from the AAS. The spherical integration of this e.i.r.p. sequence is used as a proxy for TRP.

The procedure for this measurement is as follows:

1 Set the TA and the UE in the service area of the BS. Try to use a location in the centre of the service area;
2 Start a download process on the UE, (e.g. fast.com) and make sure a high throughput is achieved;
3 Align the TA to reach maximum received power (sum over two orthogonal polarisations);
4 Record the GNSS coordinates (longitude, latitude and altitude) of the BS;
5 Record the GNSS coordinates (longitude, latitude and altitude) of the TA;
6 Make sure the UE logs GNSS coordinates versus time;
7 Move the UE to cover as large an angular region as possible, and most importantly the service area. Make sure some measurement data is recorded with the UE direction close to the TA direction to make sure the main beam power is measured;
8 Make sure the throughput to the UE is maintained;
9 While 7 and 8 are considered, measure the received power by the TA versus time.

Post processing steps:

1 Calculate the BS-TA distance using GNSS data from steps 4 and 5;
2 Get the received power time samples as the most common power level by using a histogram technique, see ANNEX 2;
3 Scale the received power time samples to e.i.r.p. time samples, by compensating for cable losses, TA gain and BS-TA distance, see Eq. (16);
4 For each e.i.r.p. time sample:
   a) Obtain the spherical coordinates of the UE as seen from the BS by using its GNSS coordinates (Step 6) and the BS GNSS coordinates (Step 4);
   b) Calculate the angular distance (great circle distance) to each centre point of the bins of a predefined grid and assign the e.i.r.p. time sample to the angular bin of smallest angular distance.
5 Within each bin (labelled by n), calculate $EIRP_n$ as the average e.i.r.p. (in linear scale, e.g., using mW or W units) of all e.i.r.p. time samples in the bin.
6 For all bins that lack measured power values, assign zero e.i.r.p.
7 Calculate TRP by a numerical integration of the binned e.i.r.p. values by using:

$$TRP_{bins} = \frac{1}{4\pi} \sum_{n=1:N} EIRP_n \, \Omega_n \tag{19}$$

Here, $EIRP_n$ is the average of all e.i.r.p. values in bin n, and Ω_n is the solid angle of bin n in steradians. The summation goes over the N bins covering the full sphere. Note, that data will be missing in most bins and set to 0 respectively. It is therefore important that the contributing data is representative.

5.3.4 Validation/example measurement with the details of equipment and settings

5.3.4.1 Method 1: Co-located UE and test antenna

The AAS was mounted at about 42 m height and directed eastwards (slightly to the north). The test points were taken along a radial route eastward at distances from 160 m to 540 m. In each test point Line of Sight (LOS) conditions were met, and scattering was well filtered out by using a high gain test antenna (TA). Final results are compared to a chamber measurement of TRP. This level was set to 0 dB which serves as a reference level for all power values. The distance from the BS to the TA was obtained from logged GNSS coordinates.

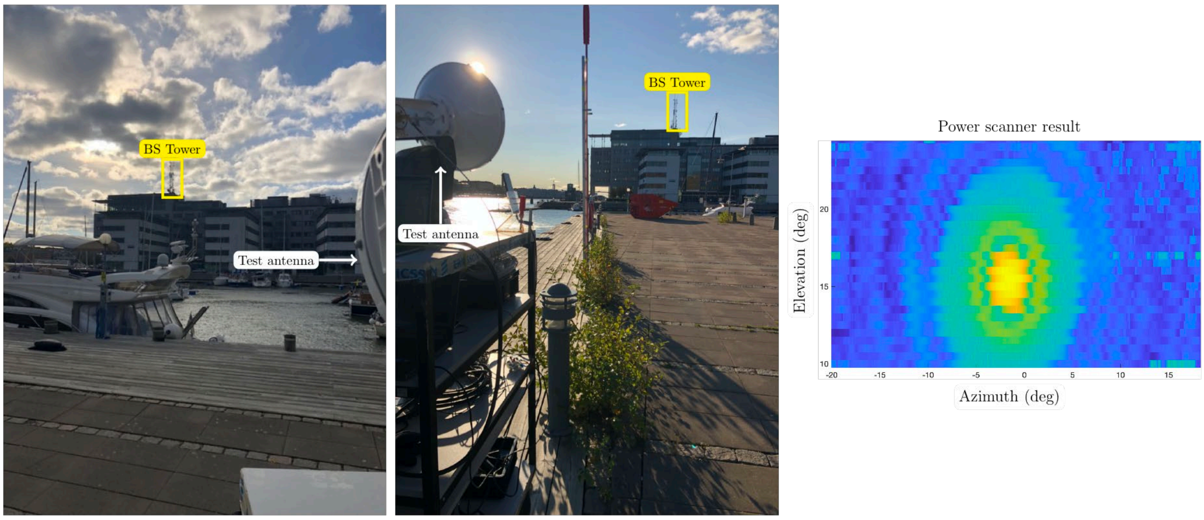


Figure 22: Photos taken from two different test locations (left and middle) with the BS mast marked with a yellow rectangle. Right: power scanner result

It is important to monitor the results from the power scanner to ensure the quality of the test result. The line-of-sight component is manifest and the scattering and interference are well suppressed by the high gain of the test antenna.

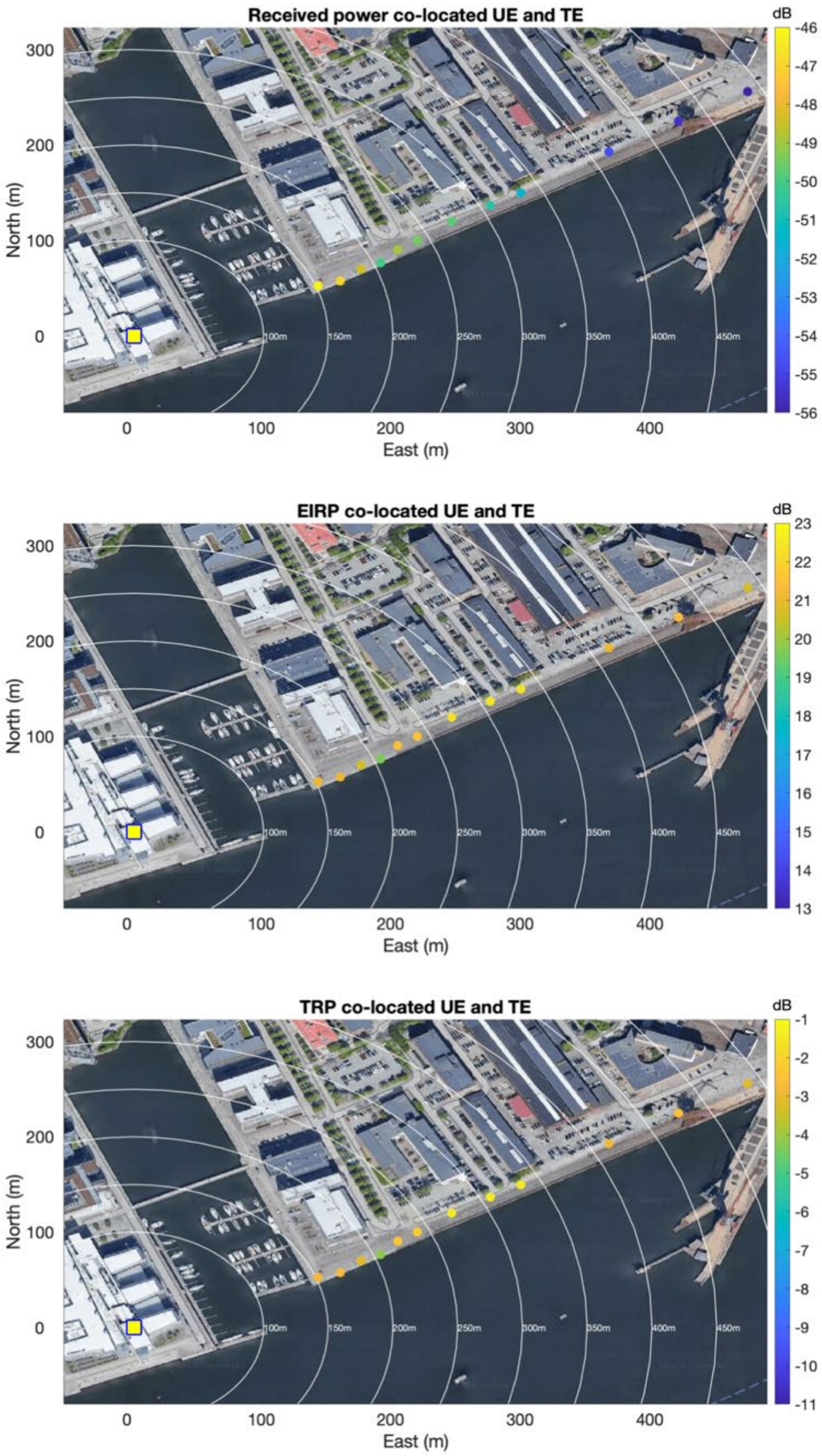
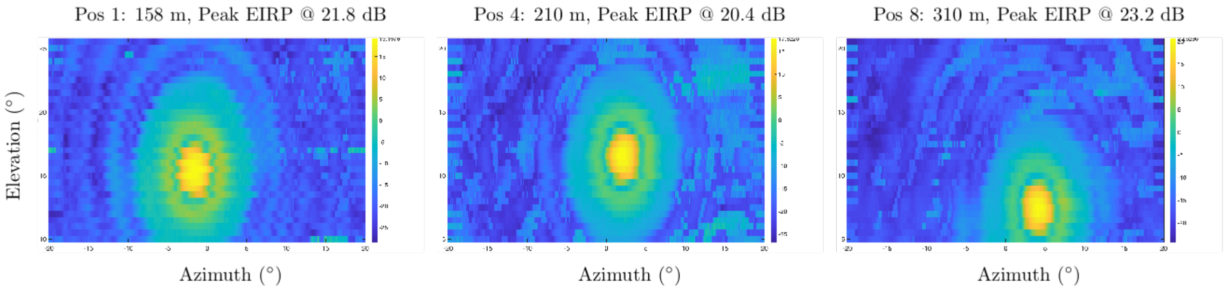
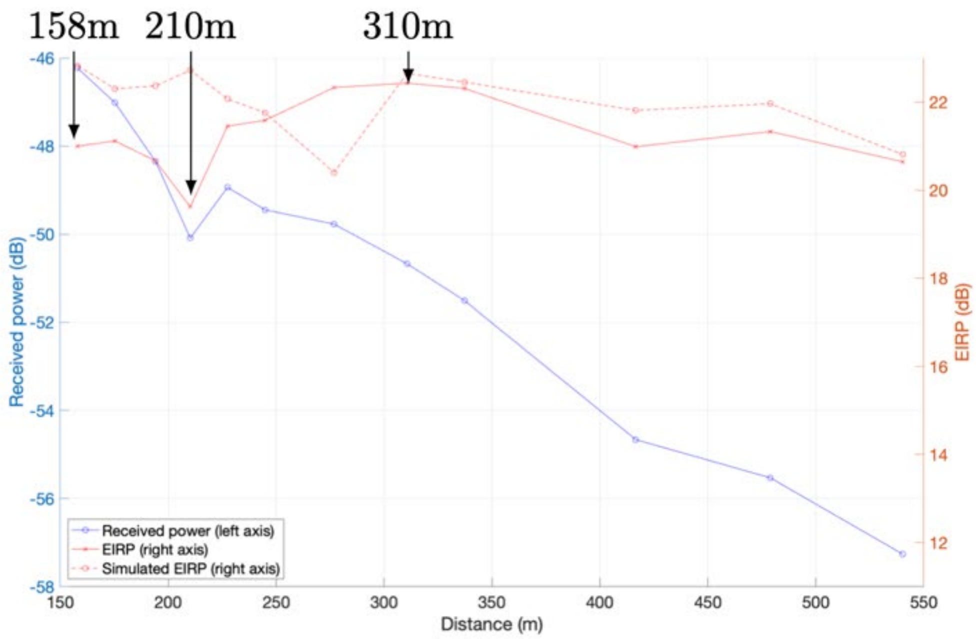


Figure 23: Received power (top), e.i.r.p. (middle) and TRP (bottom) using methodology 1 for co-located UE and TA. The BS (approx. 42 m in height) is marked as a yellow square.





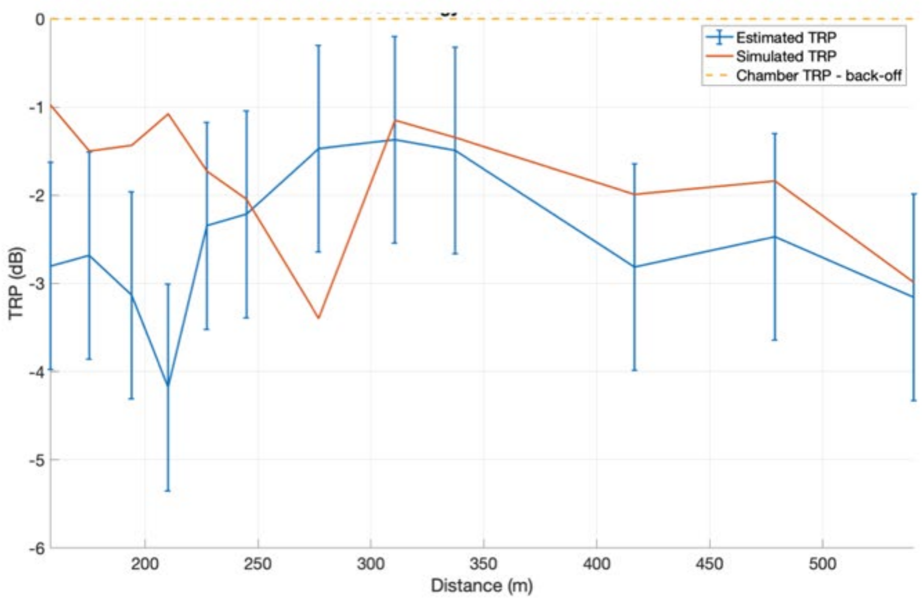


Figure 24: Received power for a set of test points away from the BS

Scanner results are shown for the closest point, the minimum e.i.r.p. point (4th point), and the maximum e.i.r.p. point (8th point in Figure 24). After transformation to TRP using the maximum directivity the variation is about 3 dB (max to min) which is about the expected directivity variation in the grid of beam layout of the AAS. Since the unknown directivity is deemed to be lower than the peak directivity of the AAS, it is reasonable to use the peak e.i.r.p. point (at 311 m) for TRP assessment.

One of the main error sources in the final result originates in the difficulty to find and assess the test point corresponding to the maximum directivity. This method also relies on knowing the directivity of the product. The power scan is a raw power scan with a narrow band filter of 2 MHz, with no de-modulation applied. The only correction is a scaling factor from the used RBW (2 MHz) to the carrier bandwidth (100 MHz). One benefit from using traffic beams for measurements is that no details about the SSB and broadcast design needs to be identified. All power is measured at peak capacity.

5.3.4.2 Method 2: Fixed UE and moving test point

This method uses a fixed UE to lock the BS radiation pattern while the TA is used to sample a part of the e.i.r.p. pattern which in turn is used to retrieve the TRP. As opposed to the first method, the directivity is not needed as input.

With the UE position fixed, and without any other traffic in the cell, should imply that the e.i.r.p. pattern of the BS is fixed in time. The TA was moved to different positions, basically along a straight line (see Figure 25). At each point the received power was measured and GNSS coordinates were logged. The GNSS coordinates of the TA and the BS were used to calculate the distance from the BS to the TA which was used to convert received power to an e.i.r.p. value for the test direction, see Eq. (15)-(17). The set of e.i.r.p. values thus forms a part of the e.i.r.p. pattern of the BS (see Figure 26).

Two different approaches are applied to obtain a TRP value from the e.i.r.p. pattern:

- (2a): In the first method a binning technique and numerical integration is used to integrate the e.i.r.p. pattern and retrieve TRP based on Eq. (19);
- (2b): In a second method, the conversion is based on the peak e.i.r.p. and the Half Power Beamwidth (HPBW) of the measured pattern.

As in Method 1, the reference 0 dB level is the TRP of the chamber measurement.

The method for numerical integration uses a set of rectangular bins in θ and ϕ covering the full sphere. Each bin is defined by its centre direction and each measurement point is assigned the closest (shortest angular distance) bin. In each bin the e.i.r.p. values are averaged and assigned to the bin. Thereafter, numerical integration is applied according to Eq. (19).

The method using the HPBW of the measured pattern uses the e.i.r.p. trace to retrieve the horizontal HPBW. In this particular case the vertical HPBW is assumed to be the same as the horizontal one. This assumption relies on knowledge of the AAS array layout or chamber measurements. It could also be retrieved by adding additional elevated or radial test points. The HPBWs are plugged into Eq. (7) to get an estimate of the AAS directivity. Finally, Eq. (17) is used to estimate TRP.

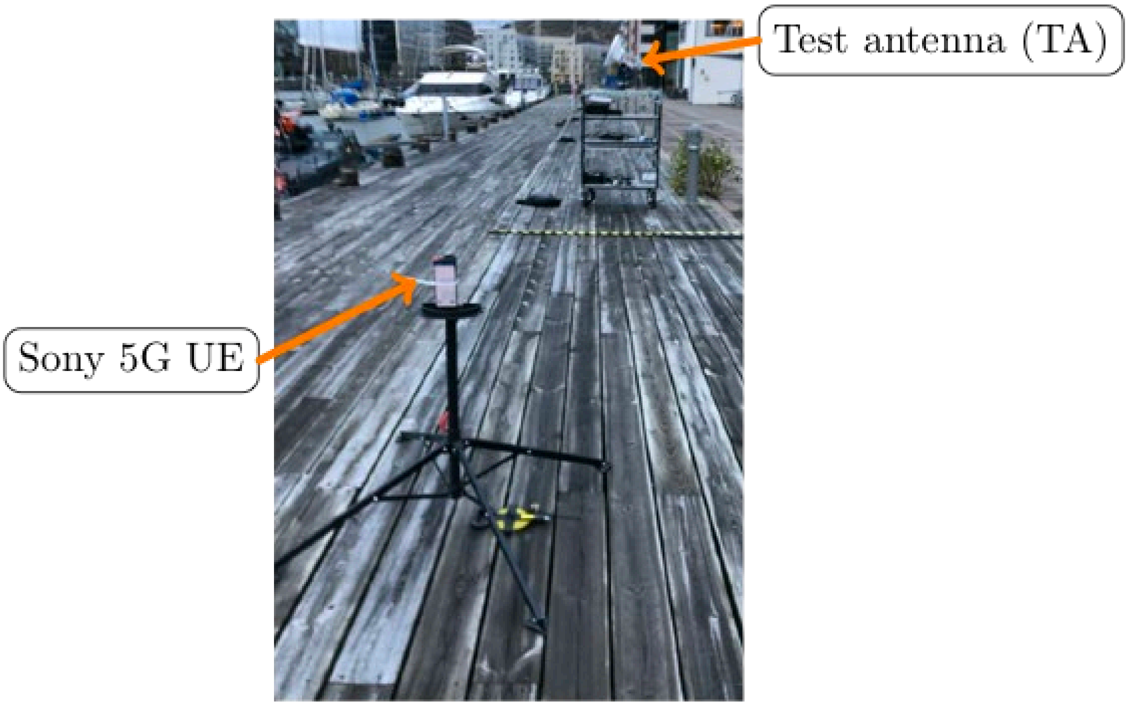


Figure 25: Setup for fixed UE and moving TA measurements

The UE was mounted on a tripod and used to generate the “best” traffic beam in the direction of the UE. The TA is used to measure the received power which is transformed to e.i.r.p. at different test locations.

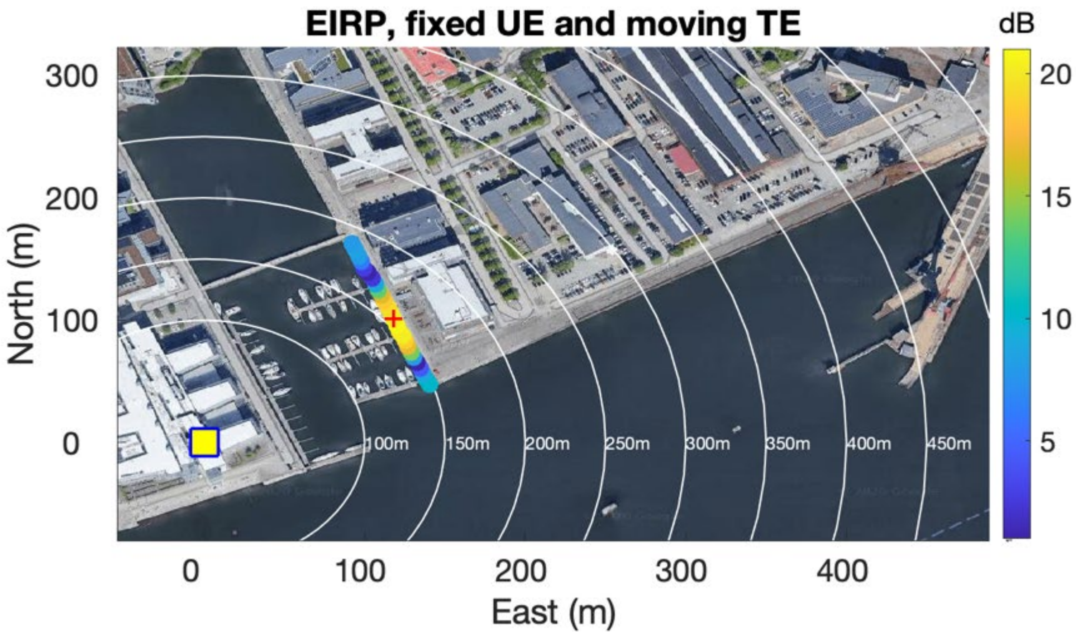


Figure 26: The UE (red +) is fixed and the scanner is moved. Received power is scaled to e.i.r.p. (peak value is about 20 dB including directivity) and displayed on the map

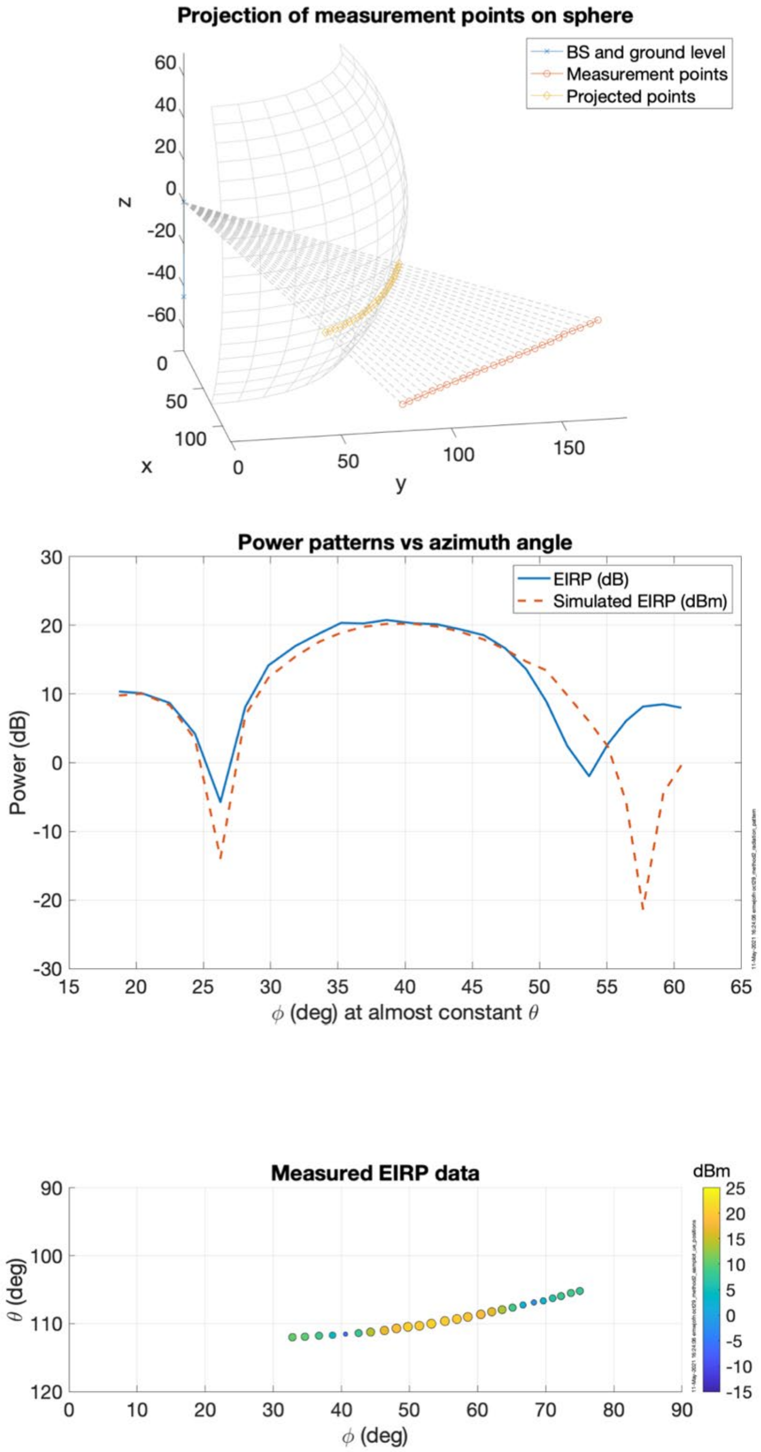


Figure 27: Measured e.i.r.p. data in BS coordinates

The upper plot in Figure 27 shows the geometric projection of the test trace (red circles) to points at a constant distance (yellow circles). The e.i.r.p. pattern is shown along the test trace (middle) and projected on a BS-centred sphere (bottom). In the middle plot, a simulated e.i.r.p. pattern is also presented.

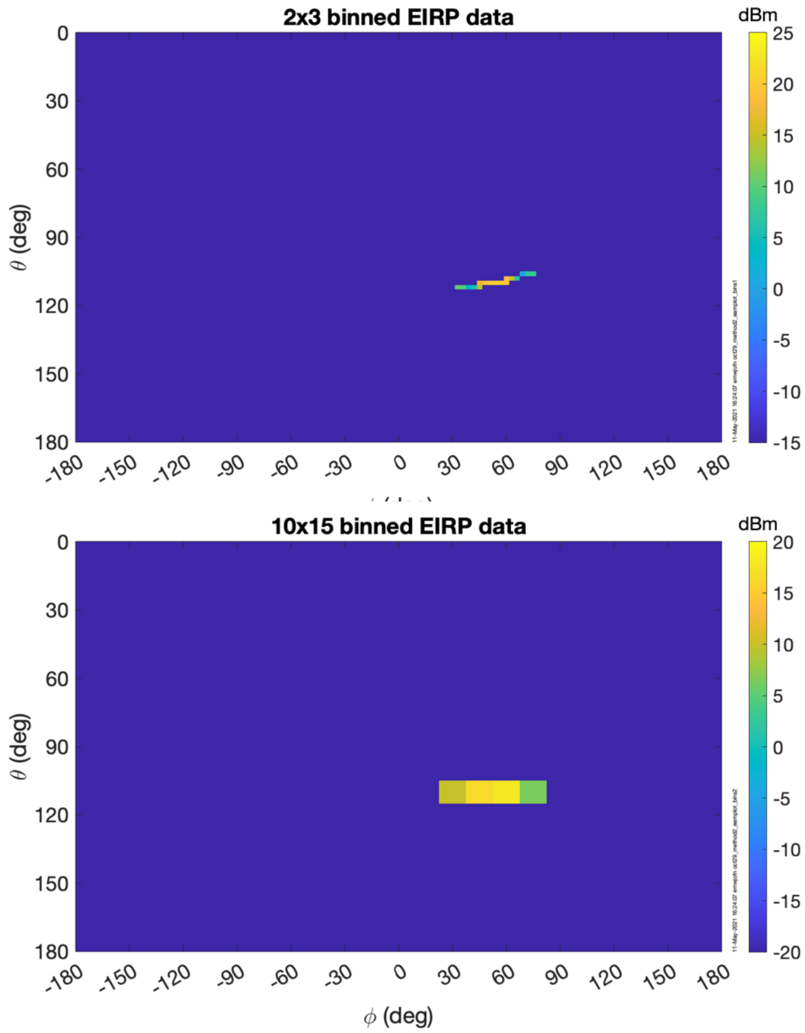


Figure 28: The measured data collected into angular bins and averaged per bin. Use of small bins (upper) and 3GPP reference step bins [13] (lower)

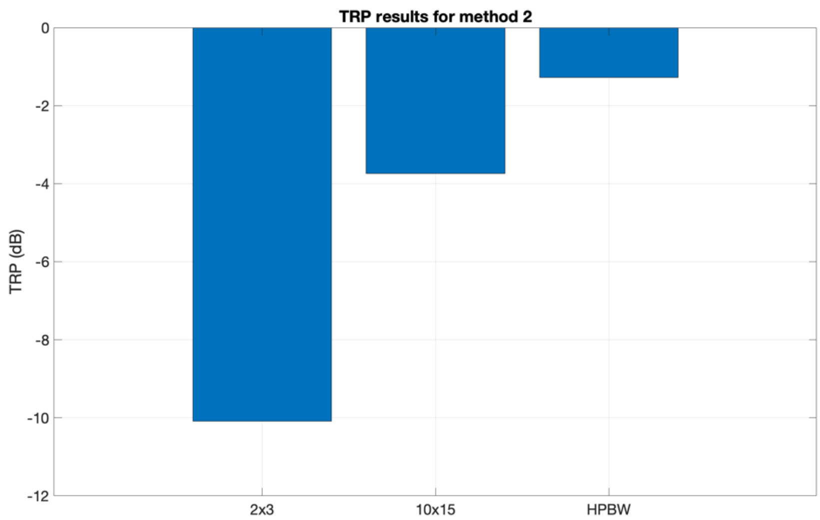


Figure 29: TRP results after numerical integration of the binned data (method 2a) and indirect via the HPBW of the measured pattern (method 2b)

When measuring only a small portion of the sphere it is important to capture the dominant angular regions, which is probably the main beam and the first side lobes. Grating lobes present a particular problem, but that is not addressed in this example. For this particular set of data only an approximately horizontal cut through the main lobe was measured.

Applying small bins in Method 2a leads to a significantly underestimated TRP. Using larger bins mitigates partially this problem in this particular case. The uncertainty of the end result depends both on selection of sampling points and the post-processing method. It is noted that a straightforward numerical integration is most probably not suited for non-regular angular grids that are indirectly used in field testing.

It should also be noted that in a chamber measurement the TRP error corresponding to using 3GPP reference steps is negligible, see [12] [13]. Here, the 3GPP reference steps are 10x15 degrees in theta and phi. The binned e.i.r.p. pattern is depicted in Figure 28 and the integrated result (TRP) in Figure 29. Note that the results are the first obtained from the field trial and the route of TA positions was taken without any knowledge of the final result.

In the Method 2b the horizontal HPBW is extracted from the measurement data and the GNSS coordinates. However, due to lack of vertical data, the vertical HPBW was set equal to the horizontal HPBW. This is based on chamber measurements and design of the AAS.

In comparison to method 1 (co-located UE and TA), the current method does not rely on declared directivity of the AAS.

The uncertainty of the assessment is subject to further investigation.

5.3.4.3 Method 3: Moving UE and fixed test point, result examples

The measurement route and the received power is depicted in Figure 30. The sum of two orthogonal polarisations and cable losses is accounted for.

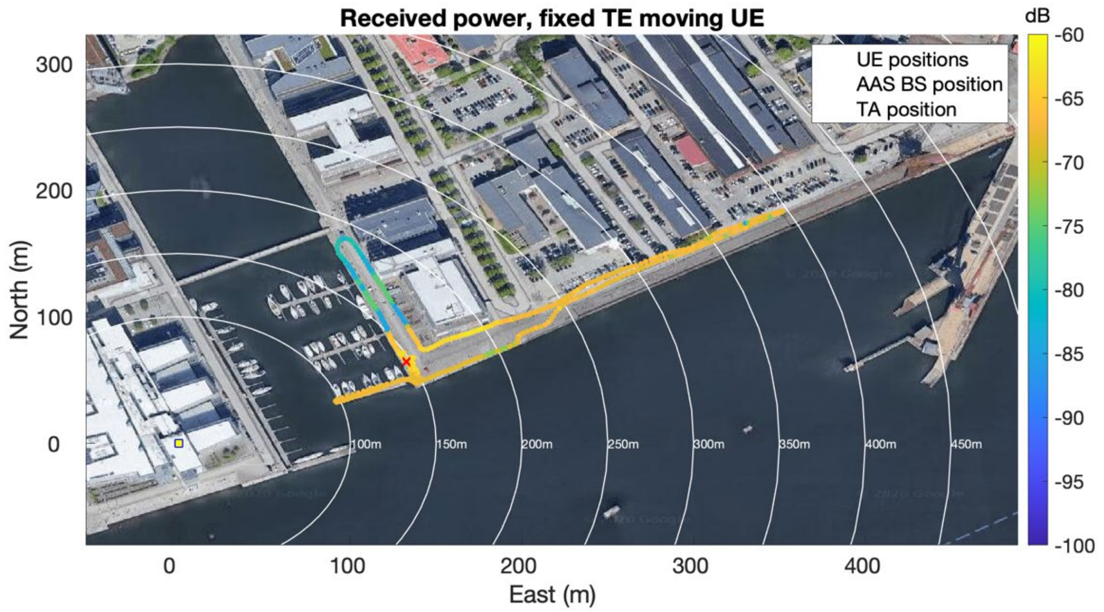


Figure 30: Measurement route of UE. The TA is located at a fixed position (red cross) and the BS at approx. 42 m height is depicted as a yellow square. The colour indicates the received power at the TA port, and each dot is placed at the simultaneous location of the UE

By synchronising the time of the UE position data to the time scale of the power data, the power per UE position is obtained. For each UE position the average downlink power is calculated. The received power will be a mixed signal, containing SSB, broadcast and traffic data. To simply take the time average will therefore not give a representative power value for the traffic data. In order to handle this, without de-modulating the data, a histogram technique is used to find the most common level. This power level is used as an estimate of the power level of the downlink traffic data. The UE positions is converted to a direction relative to the AAS BS (see Figure 31). The power value is scaled to e.i.r.p. by distance and TA gain.

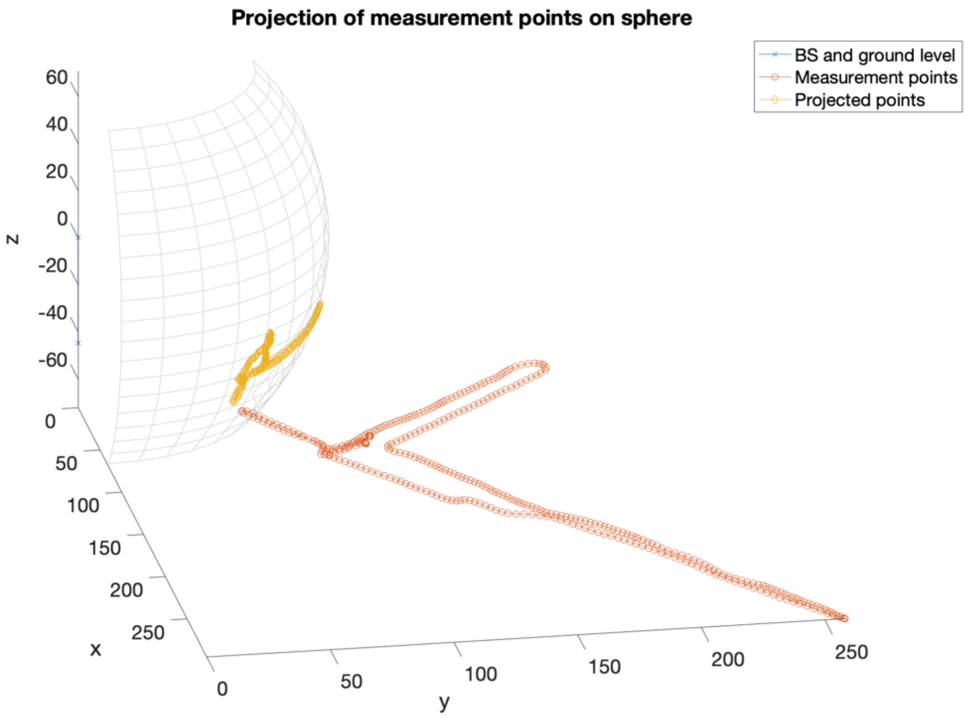


Figure 31: Projection of UE positions in Method 3 on a sphere, used for angular binning of data. The blue dots represent the ground level at -42m and the BS at 0m. All axes are in metres

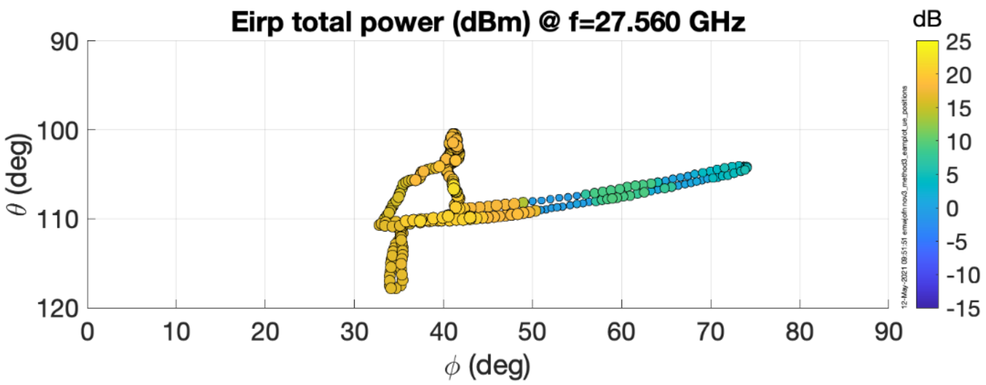


Figure 32: Received power converted to e.i.r.p. at UE angles θ and ϕ in Method D-3

Finally, for each angular bin, all power values are averaged and assigned to the bin (see Figure 33 and Figure 34), and standard spherical integration is used to calculate a TRP estimate as in Method 2. The final result depends on the angular bin size, test route, and the extrapolation used for bins with no data (see Figure 35).

In a street level measurement, only a small part of the e.i.r.p. pattern can be measured. However, for in-band signals a manifest main lobe should appear. Most of the power will be radiated through the main beam and the remaining power can be thought of as the average sidelobe power radiated through the sidelobe regions. Two approaches are implemented to take into account the unused bins: In the first method the unused bins are populated with zero data, and in a second approach a sidelobe level is calculated as the average of all bins at least -13 dB below the peak bin. This level is then used for all bins that lack measured power values.

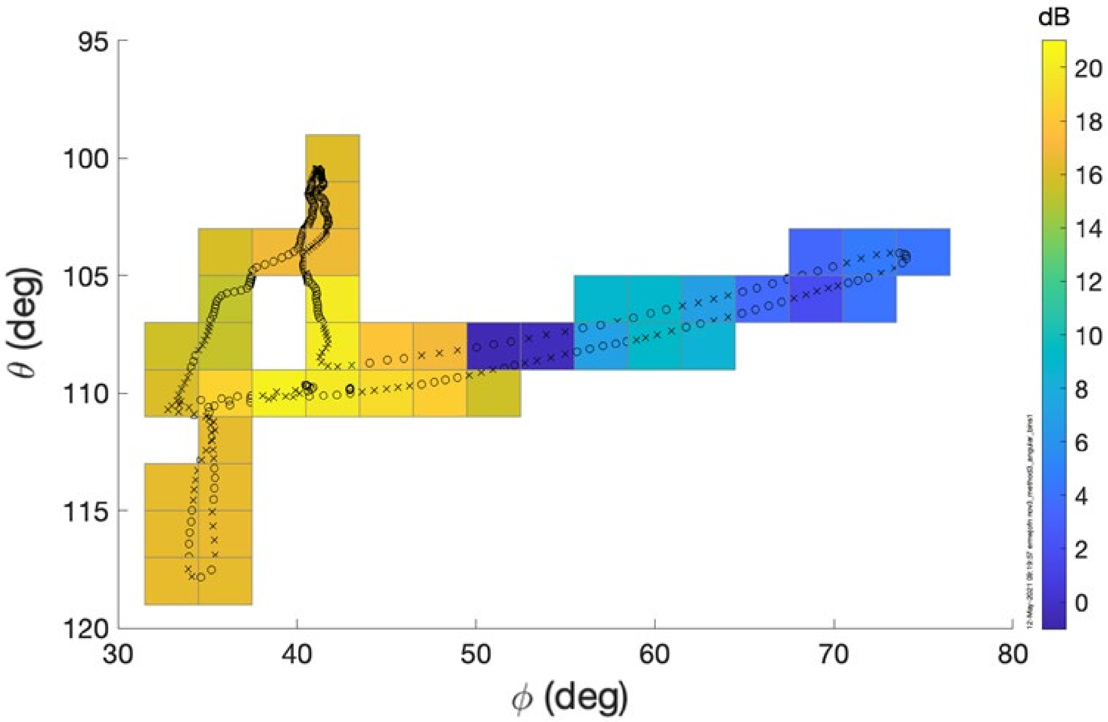


Figure 33: Assignment of beam directions to angular bins for a 2x3 grid

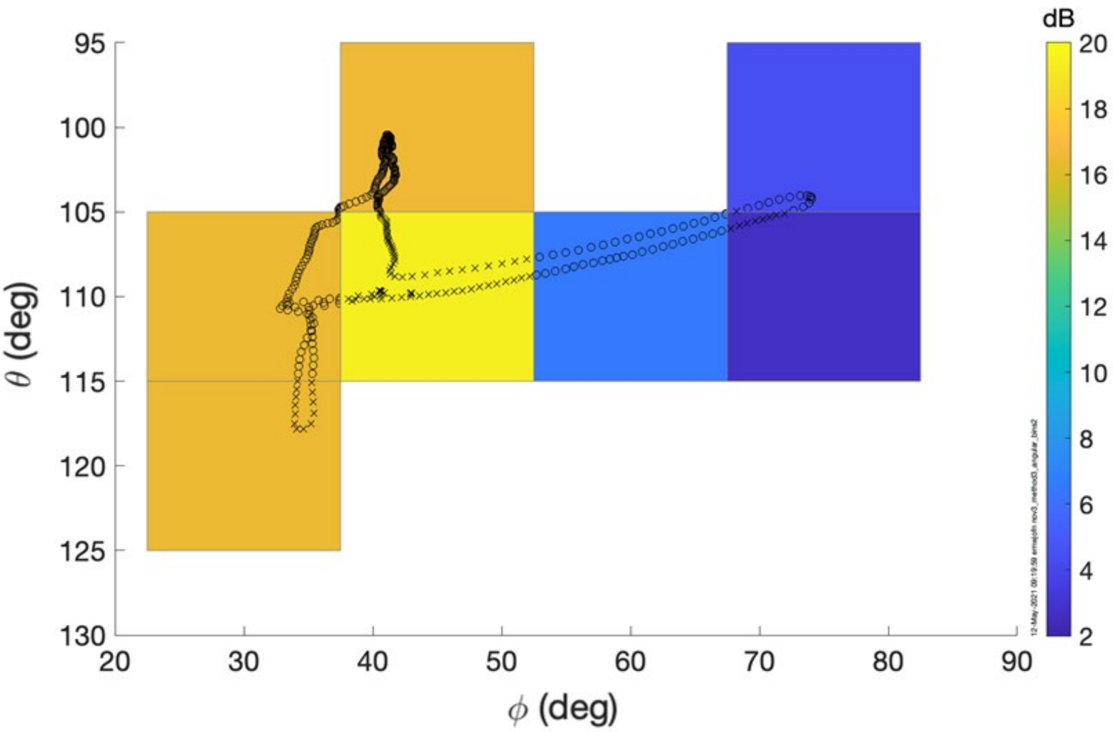


Figure 34: Binning of e.i.r.p. data using 3GPP reference steps for TRP assessment

In the case of 10x15 degrees as defined as the 3GPP reference steps [13], more samples are assigned per bin, compared to the grid used in Figure 33, but the end result turns out to be closer to the true value for this measurement.

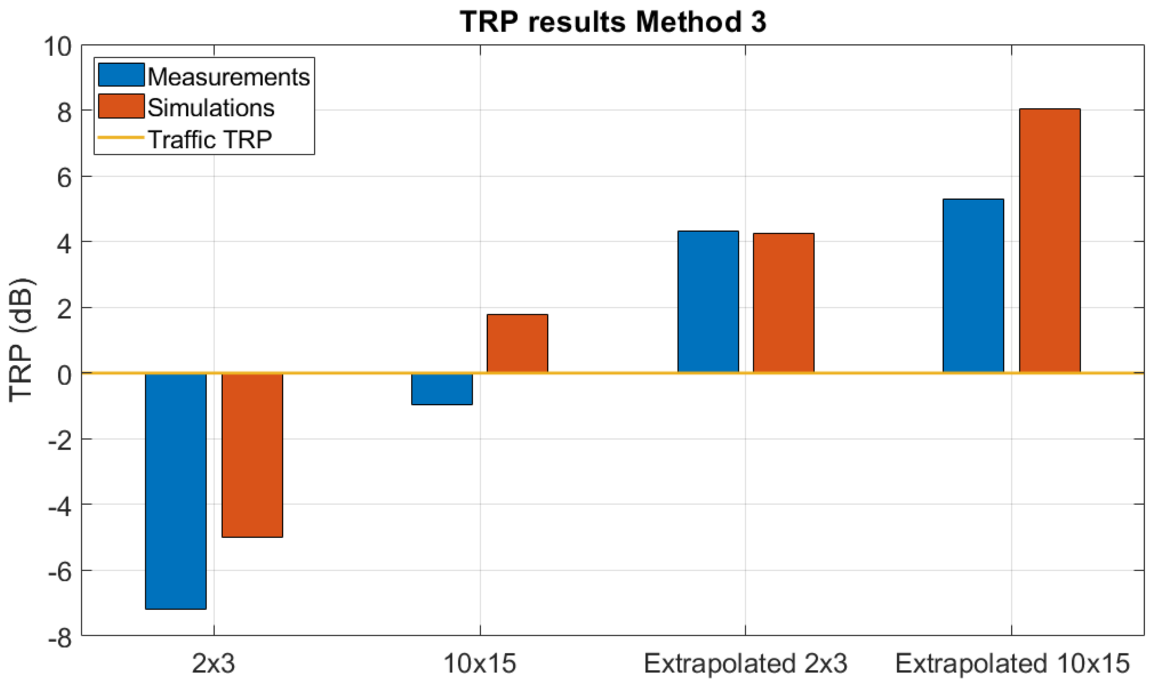


Figure 35: Initial Method 3 TRP results. The two leftmost results have used zero-value for unused bins, while the two rightmost results ("Extrapolated") have used an average sidelobe-level for all bins that lack measured power values

Initial handheld measurements were performed using method 3. It is seen in Figure 35 that these measurements can be simulated with good accuracy. Simulated results are used for the following discussion. In the simulations, it is assumed that a test UE is moved on a spherical surface in the service area of the BS, mounted on a drone. It is important to choose the size of the post-processing bins, such that there are samples assigned to each bin. Two different aspects of the measurement setup are considered: placement of the test antenna in the cell and the effect of presence of other UEs in the cell during the test.

5.3.5 Simulation-based validation of methodology

5.3.5.1 Simulation of placement of the test antenna in the cell

The position of the test antenna in the cell will affect the TRP proxy. To capture the power radiated in the cell in the best way, the test antenna should be placed at the centre direction of the cell. To show the effect of the test antenna position, two cases are compared: (a) test antenna in the middle and (b) the edge of the cell, respectively. The simulated power at the test antenna is plotted in Figure 36 and TRP proxy for these two cases is depicted in Figure 37.

For the results in this section, it is assumed that the bins out of cell are filled with zero values. Therefore, the TRP proxy underestimates the full-sphere TRP (normalised to 0 dB level). Additional underestimation is seen when the test antenna is placed on the edge of the cell. This is because in this case the proxy pattern is truncated non-symmetrically and near sidelobes on one side are omitted while on the other side further sidelobes with lower power are taken into the calculation, see Figure 36 for comparison.

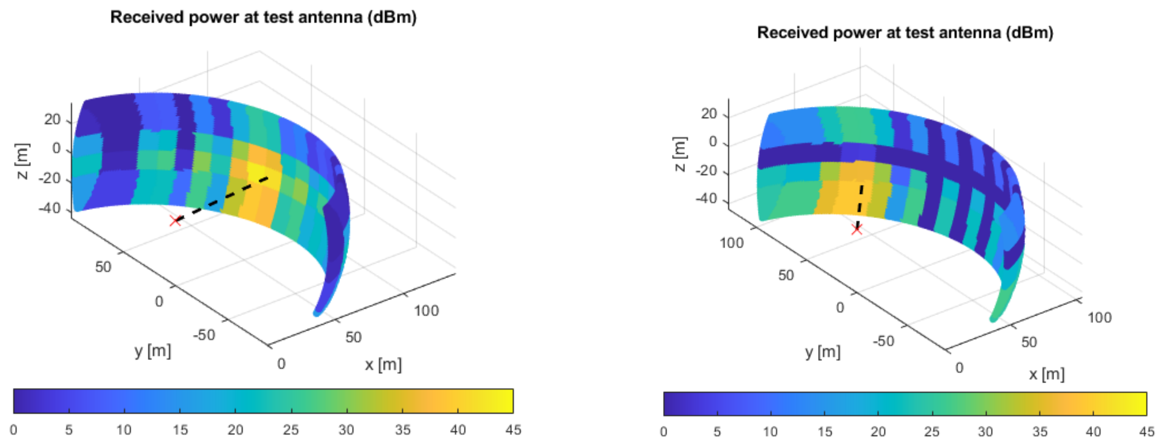


Figure 36: Simulation of the measured power at the test antenna, vs the drone positions. The test antenna is placed at the middle of the cell (left) and the edge of the cell (right). The direction from the BS (red cross) towards the test antenna is shown with the dashed black line

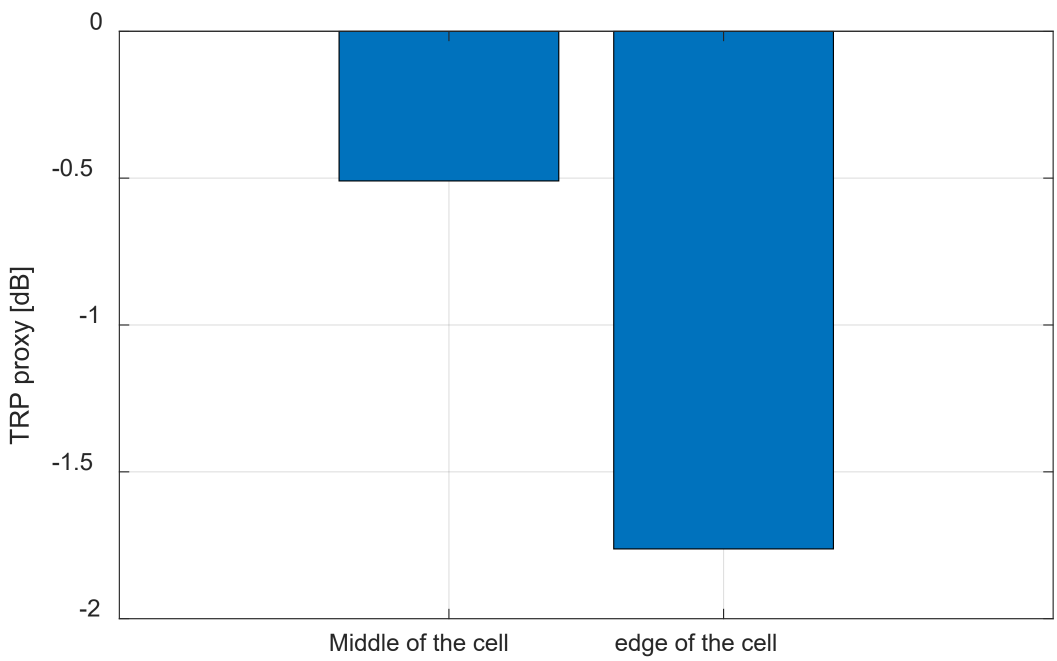


Figure 37: Simulation of TRP proxy for different positions of the test antenna in the cell. The 0 dB level corresponds to full-sphere TRP

5.3.5.2 Simulation of other UEs in the cell

Figure 38 shows the simulated scenario where the test antenna, shown with the yellow pin, is placed in the centre of the cell. The test UE is moving on a spherical surface in the cell, shown with the yellow arc. The blue lines show a 120° sector. Three scenarios are considered for the second UE. In scenario (a) it is stationary during the test, in scenario (b) it is moving on a path not close to the test antenna, while in scenario (c) the UE is moving in the vicinity of the test antenna. The stationary position as well as the paths of the second UE are shown with green markers in Figure 38. In the simulations, it is assumed that the cell resources are divided equally between the two UEs.

Figure 38: Simulated placement of the test antenna and the secondary UE position in method 3

The effect of the second UE on the TRP proxy is shown in Figure 39.

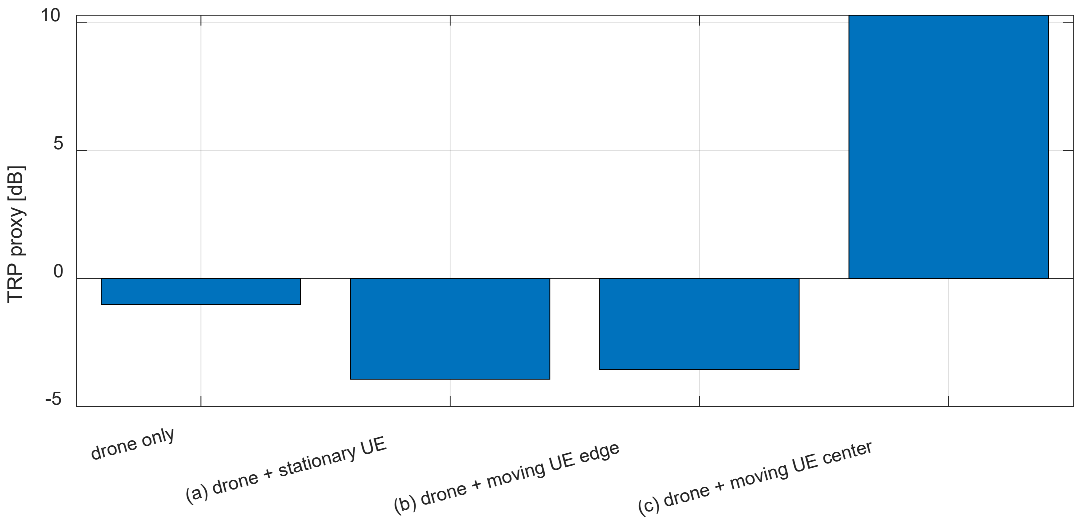


Figure 39: Simulated TRP proxy estimation in the presence of other UEs

It is observed that the result can be affected by the presence of other UEs in the cell. A UE close to the test antenna will increase the TRP proxy value while a UE farther away will decrease the TRP proxy. Presence of more UEs in different areas of the cell can cancel out each other's effect in the averaging post-processing step. To minimise the effect of other UEs, the test UE should be forced to download large amounts of data in order to consume a larger part of the cell resources, and the effect of close UEs should be mitigated. If further time synchronised information is available, either at the UE or the BS, the power samples corresponding to the other UEs can be filtered out from the data.

5.3.6 Summary for the methods tested

Preliminary results from a field trial demonstrate the possibility to measure TRP using street level power density measurements. Test examples presented in this report are from measuring BS operating in the 26.5- 29.5 GHz band, but the methods are applicable to other frequency bands. The high gain of the test antenna (TA) is important, but analysis on how much the TA gain can be relaxed has not been done. An alternative way of discriminating channel effects is of course to get closer using e.g. drones. The final TRP result is compared to chamber measurements and the output power settings are probably not identical to the ones used in the field.

For in-band measurements, a single point measurement (method 1) can be used with the knowledge of peak directivity. However, using multiple points (in line-of-sight conditions) provides a sanity check and gives a rough feeling of the uncertainty of the method. It also helps to find the “best” test point corresponding to peak directivity.

If the directivity is not known, several test points must be used. Two different approaches have been shown. In Method 2a the result depends on the post-processing and adequate handling of the independence of the data samples. Vertically or radially distributed test points would probably help here.

In Method 2b the test points should probably also have been distributed radially or vertically, preferably using drones.

In a third method the TA is fixed and the UE is moving, implying a moving beam. A TRP proxy is then calculated as an average over beams, and possibly some TA locations, using adequate post-processing to avoid over-representation of dependent power samples. Initial results for street level UE positions show low estimates of TRP which can most probably be improved by using elevated UE positions or using a flying drone to move the UE. It’s important to follow the recommendations on the test antenna placement in the cell and bin size for post-processing. Furthermore, some techniques to mitigate the effect of other UEs have been identified.

6 CONCLUSIONS

The elaboration on possible issues and properties of 5G AAS base stations proves that over-the-air measurements of their emissions are extremely challenging and, in many aspects different from measurements of systems with passive antenna systems.

Depending on the required result, purpose of the measurement, knowledge of certain RF parameters, possible test modes of the base station, and available equipment, there is no single suitable measurement method covering all cases. Instead, the final approach to the measurement needs to be based on a combination of the signals to be measured, available a-priori information and measurement equipment.

This Report contains case studies of three practical measurements with different combinations of the above. These are:

- Ground-based measurement of the broadcast and synchronisation signal in normal operating mode of the base station;
- Airborne measurement of the broadcast and synchronisation signal as well as the traffic signals with a drone while the base station is in a test mode, over a static beam;
- Ground-based measurement by attracting a traffic beam with an active user equipment while the base station is in normal operating mode.

All three presented methods achieved good results with reasonable accuracy.

To specify reliable values for representative measurement uncertainty, more measurements are necessary. From current experience the uncertainties can be estimated to be in the order of 2-4 dB.

This Report has addressed measurements of in-band power of AAS. Further work is necessary to investigate suitable methods for the unwanted emissions of AAS and for different deployment scenarios.

ANNEX 1: SELECTION OF TEST ANTENNA

The gain and the beamwidth of antennas are dependent, and inversely proportional, i.e.

$$G = \frac{\mathrm{C}}{\mathrm{HPBW}_{\theta} * \mathrm{HPBW}_{\phi}} \tag{20}$$

where C is a constant which depends on the antenna type. Properties of TAs for field measurements are easier to describe in terms of beamwidth and the gain of the TA is hence implicitly defined. The Half Power Beamwidth (HPBW) is by definition the width of the angular region within the main lobe wherein the gain is at least 50% of the peak gain. The main lobe of the antenna radiation pattern is typically wider. In antenna chamber measurements [14], covering the test object with the HPBW is deemed to be good enough for accurate measurement results. In field measurements, the purpose of the TA is to detect the Line of Sight (LoS) signal from the base station in the presence of scattered and interfering signals. Scattered signals may come from buildings, ground, open water etc. One of the most challenging signals to suppress is the ground reflection.

In order to suppress scattering from the environment the TA HPBW should cover just the BS and nothing else (see Figure 40). However, this leads to very narrow HPBW and extremely high gain values in field testing scenarios, due to the much larger testing distance. Moreover, proper alignment will be quite challenging.

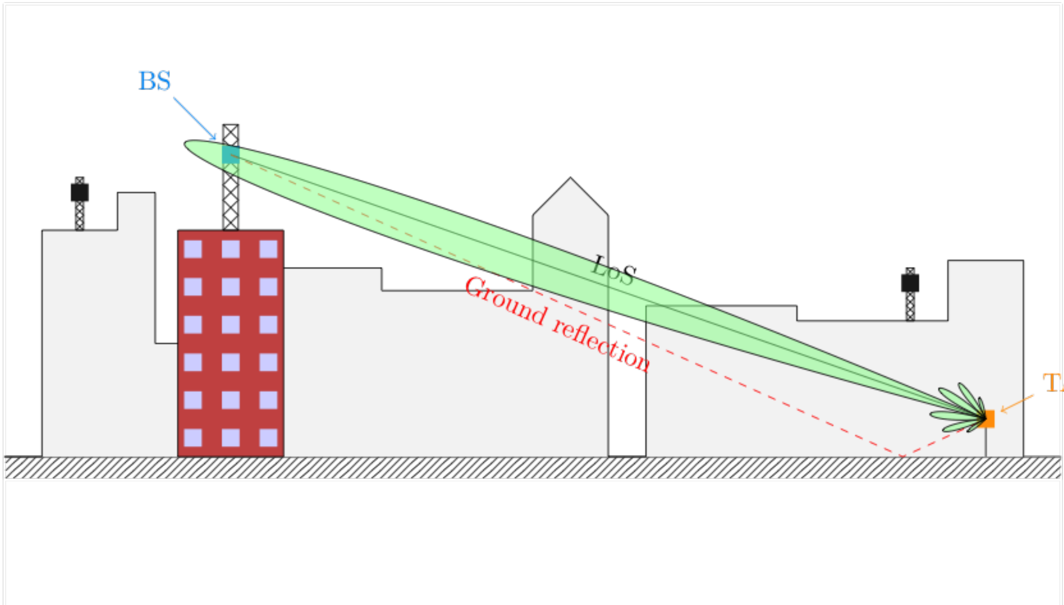


Figure 40: Illustration of optimal scattering suppression by using a high gain TA with a narrow beam, selected to just cover the BS. Note that that interfering signals such as the ground reflection is suppressed by the relatively small gain in the sidelobes of the TA. The green area depicts the radiation pattern of the TA

A pragmatic criterion for TA selection is to cover the BS, any BS tower, and a fraction of the building it is mounted on. In addition, the ground reflection should be suppressed by receiving it within the sidelobe region of the TA (see Figure 41). To ensure LoS conditions, scatterers within the first Fresnel zone should be avoided.

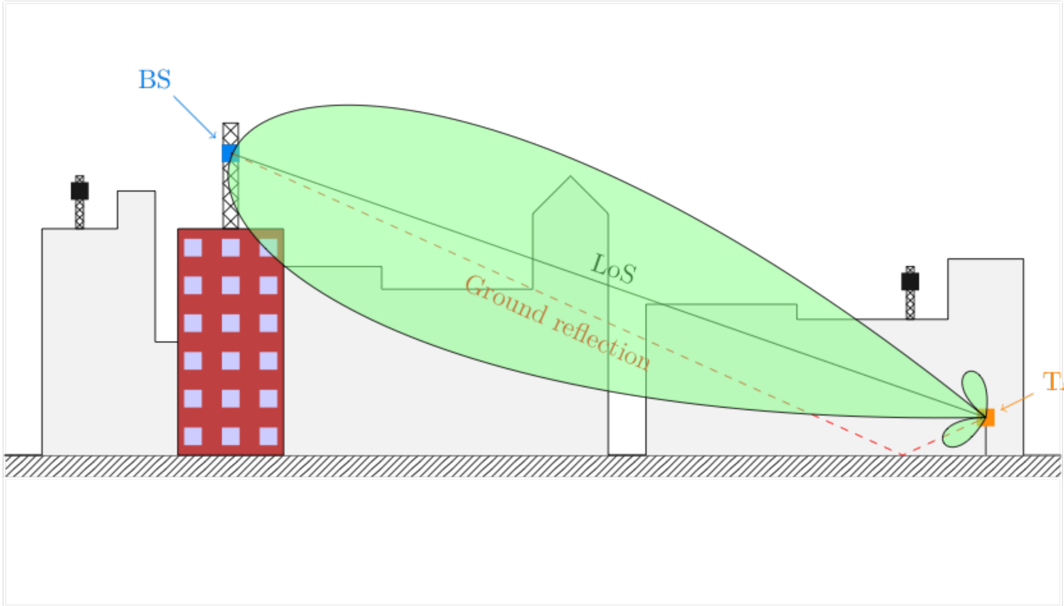


Figure 41: Illustration of recommended beamwidth of TA. The main beam covers the antenna tower and a fraction of the building, and the ground reflection is received by a sidelobe, and hence suppressed. Note, that at large distances the ground reflection will be received in the main beam. Hence, each TA has a range of distances for proper operation

Figure 42 illustrates the effect of using a too large beamwidth. In this scenario the requirements on alignment can be relaxed. On the other hand the desired signal is contaminated with the ground reflection, other scattering effects and signals from other cells.

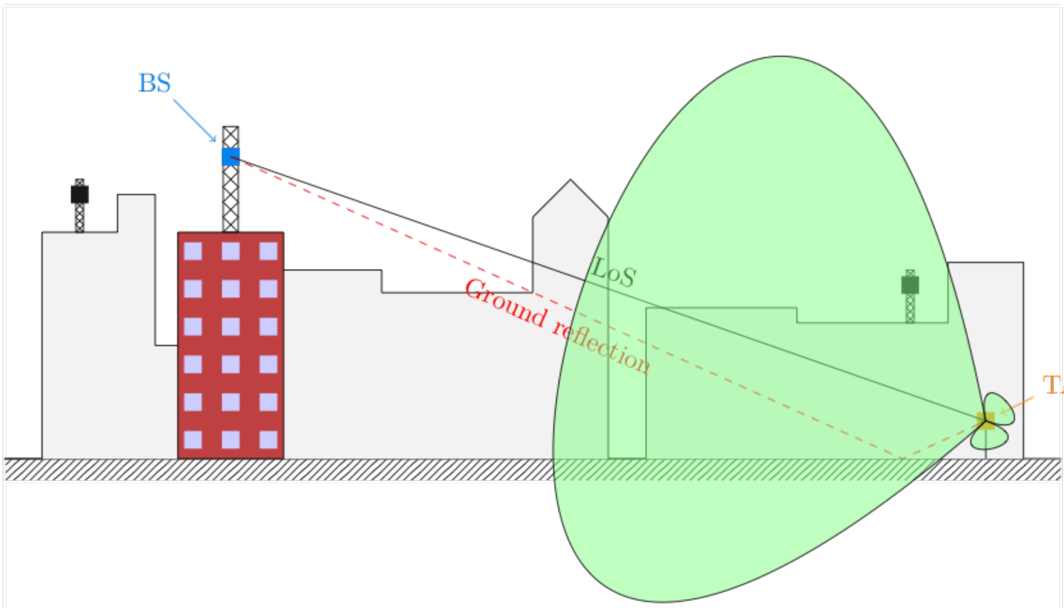


Figure 42: Use of a too wide main beam (low gain TA) leads to large measurement errors due to interference, here ground reflection and interfering signals from other cells

To summarise the above observations:

Use a high gain antenna with a HPBW that covers:

- The BS antenna;
- The BS tower;
- Fractions of the building the BS is mounted on.

And does not cover:

- The ground;
- Neighbouring buildings;
- Other BS towers.

Note: the height of the TA over ground can help in suppressing ground reflections as well as keeping the ground and other interferers out of the first Fresnel zone.

ANNEX 2: DETECTION OF TRAFFIC POWER LEVELS WITHOUT DEMODULATION

When using a UE to trigger traffic data, the power level can be retrieved as the most common power level. To do this:

1 Divide all time samples into *time bins*[1];

2 Convert power values to logarithmic scale (dB);

3 In each time bin,

- sort the data in a set of *power level bins* equally spaced in dB. (The reason for using a logarithmic scale is the high dynamic range of the received power levels);
- Identify the *power level bin* containing the largest number of samples;
- Determine the traffic power level as the midpoint power level of the identified bin.

Two examples are given below. In the first example, the traffic power is in the upper part of the dynamic range, which is typical in e.g. the main lobe (see Figure 43 and Figure 44). In a second example the received power is in the lower part of the dynamic range, which is typical for a sidelobe measurement (see Figure 45 and Figure 46).

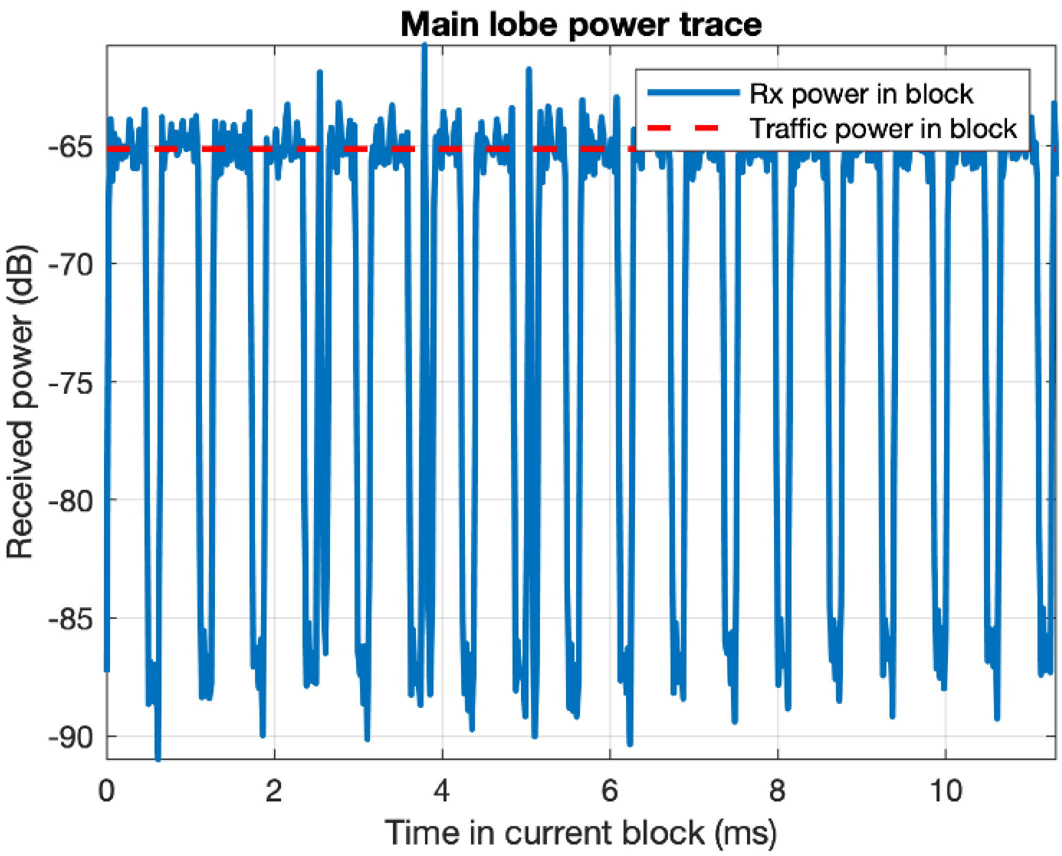


Figure 43: Received power levels in one time block containing 500 samples detected at 44.1 kHz rate. The most common power value, the traffic power, is depicted by a red dashed line. This value is detected using a histogram technique (see Figure 44)

[1] In the given examples a sampling rate of 44.1 kHz and 500 samples per bin is used, corresponding to 11.3 ms/bin

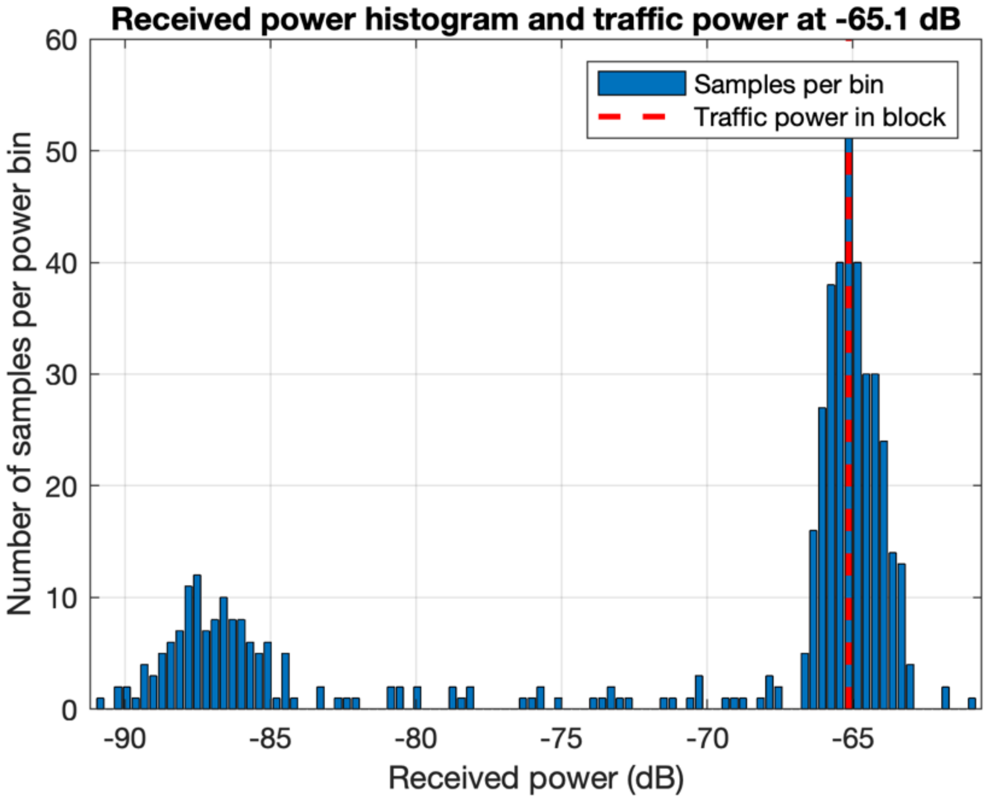


Figure 44: The data of Figure 43 as a histogram. The traffic power is determined as the bin containing the most samples. In this case the traffic power is significantly higher than the SSB power

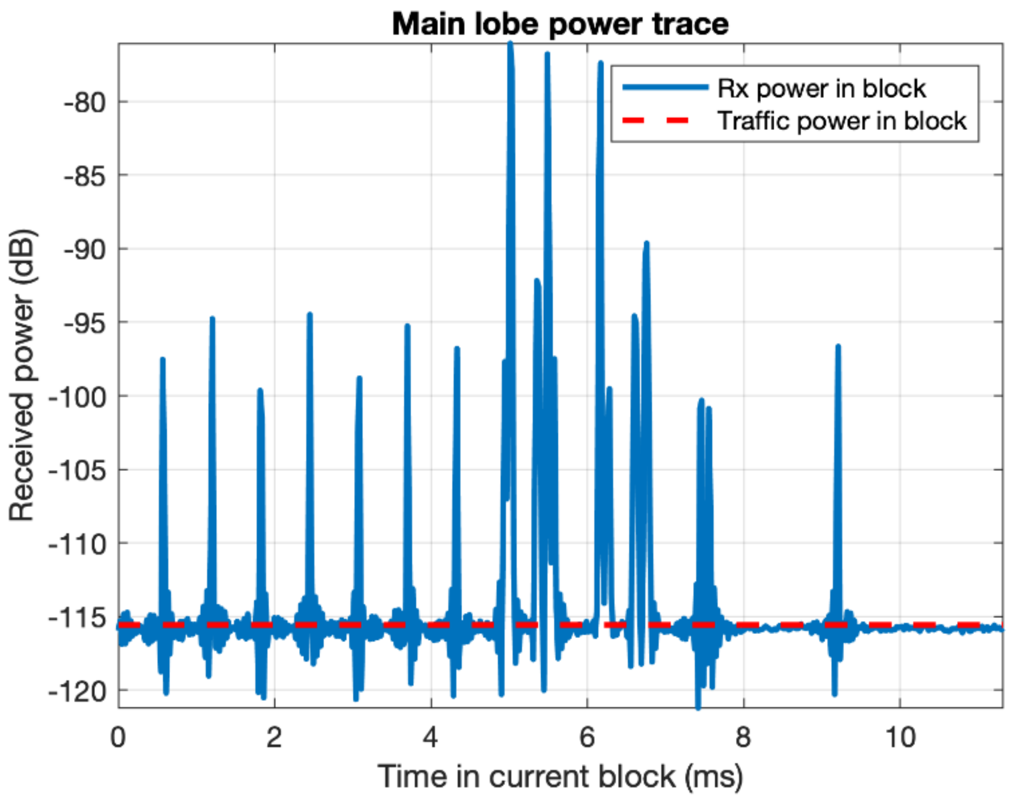


Figure 45: Received power levels in a time block corresponding to a sidelobe region of the traffic beam. The most common power value is here in the lower end in the range of detected power values within the block. This value is detected using a histogram technique (see Figure 46)

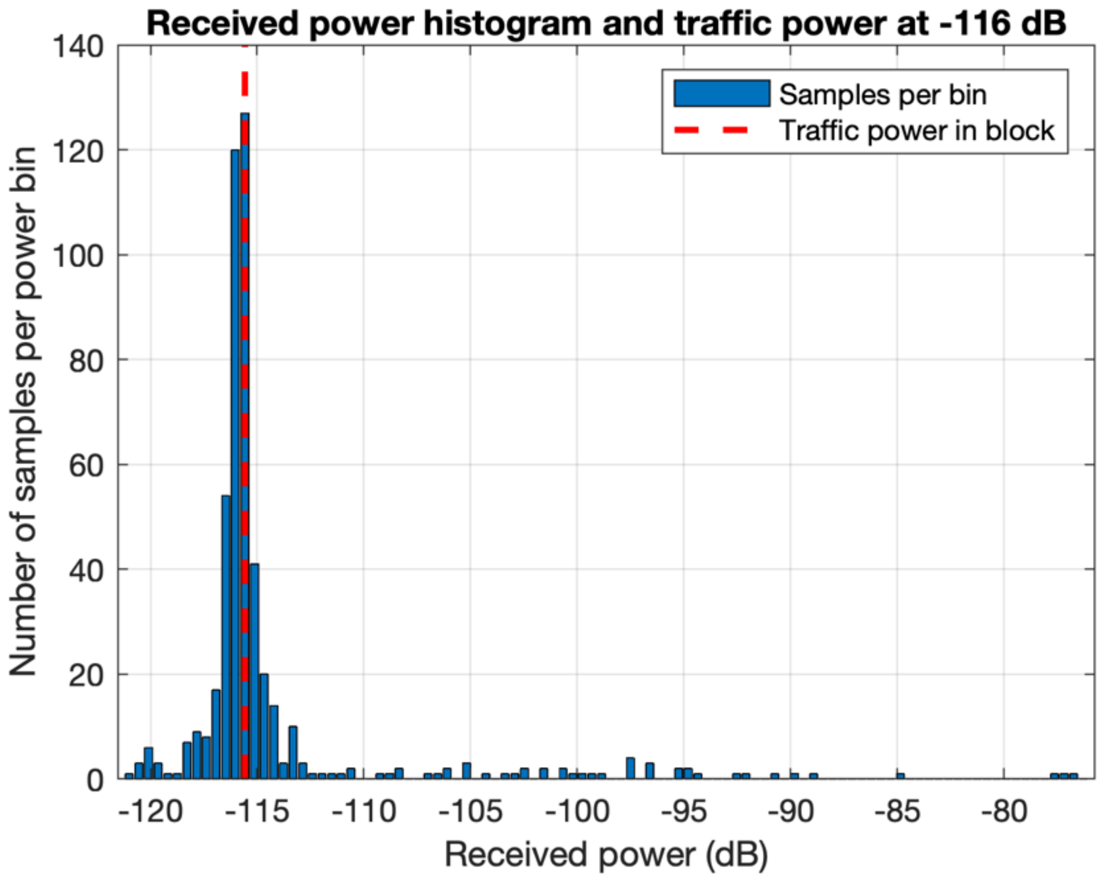


Figure 46: The data of Figure 45 depicted as a histogram. The traffic power is here determined as the bin containing the most samples. Pure average calculation would introduce a significant error

ANNEX 3: LIST OF REFERENCES

[1] ECC Decision (05)05: "ECC Decision of 18 March 2005 on harmonised utilisation of spectrum for Mobile/Fixed Communications Networks (MFCN) operating within the band 2500-2690 MHz", corrected March 2022

[2] Commission Implementing Decision (EU) 2020/636 of 8 May 2020 amending Decision 2008/477/EC as regards an update of relevant technical conditions applicable to the 2500-2690 MHz frequency band

[3] ECC Decision (06)01: "ECC Decision of 24 March 2006 on the harmonised utilisation of the bands1920-1980 MHz and 2110-2170 MHz for mobile/fixed communications networks (MFCN) including terrestrial IMT", latest amended March 2019

[4] Commission Implementing Decision (EU) 2020/667 of 6 May 2020 amending Decision 2012/688/EU as regards an update of relevant technical conditions applicable to the frequency bands 1920-1980 MHz and 2110-2170 MHz

[5] ECC Decision (11)06: "ECC Decision of 9 December 2011 on harmonised frequency arrangements and least restrictive technical conditions (LRTC) for mobile/fixed communications networks (MFCN) operating in the band 3400-3800 MHz", latest amended October 2018

[6] Commission Implementing Decision (EU) 2019/235 of 24 January 2019 on amending Decision 2008/411/EC as regards an update of relevant technical conditions applicable to the 3400-3800 MHz frequency band

[7] ECC Decision (18)06: "ECC Decision of 6 July 2018 on the harmonised technical conditions for Mobile/Fixed Communications Networks (MFCN) in the band 24.25-27.5 GHz", latest amended November 2020

[8] Commission Implementing Decision (EU) 2020/590 of 24 April 2020 amending Decision (EU) 2019/784 as regards an update of relevant technical conditions applicable to the 24.25-27.5 GHz frequency band

[9] ERC Recommendation 74-01: "ERC Recommendation of 1998 on unwanted Emissions in the Spurious Domain", latest updated October 2021

[10] CEPT Report 67: "Report A from CEPT to the European Commission in response to the Mandate to develop harmonised technical conditions for spectrum use in support of the introduction of next-generation (5G) terrestrial wireless systems in the Union, Review of the harmonised technical conditions applicable to the 3.4-3.8 GHz ('3.6 GHz') frequency band", approved July 2018

[11] 3GPP TS 37.145-2 V17.4.0: "Active Antenna System (AAS) Base Station (BS) conformance testing; Part 2: radiated conformance testing"

[12] J. Friden, A. Razavi and A. Stjernman, "Angular Sampling, Test Signal, and Near-Field Aspects for Over-The-Air Total Radiated Power Assessment in Anechoic Chambers": https://ieeexplore.ieee.org/document/8470084

[13] 3GPP TR 37.941 V17.0.0: "Radio Frequency (RF) conformance testing background for radiated Base Station (BS) requirements"

[14] "IEEE standard test procedure for antennas", IEEE, 1979

[15] ITU-R Report SM.2056: "Airborne verification of antenna patterns of broadcasting stations".

[16] ITU-R Recommendation P.525: "Calculation of free-space attenuation"

[17] Antenna Theory: Analysis and Design, 3rd Edition, C.A. Balanis, Wiley , page 51

[18] ECC Decision (06)13: "ECC Decision of 1 December 2006 on harmonised technical conditions for mobile/fixed communications networks (MFCN) including terrestrial IMT systems, other than GSM and EC-GSM IoT, in the bands 880-915/925-960 MHz and 1710-1785/1805-1880 MHz, latest amended 4 March 2022

[19] Commission Implementing Decision (EU) 2022/173 of 7 February 2022 on the harmonisation of the 900 MHz and 1800 MHz frequency bands for terrestrial systems capable of providing electronic communications services in the Union and repealing Decision 2009/766/EC