Technical Report: Measurement Method for 5G NR Base Stations up to 6 GHz

18 February 2020

(Version 2.1 from 20 April 2020)

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www.metas.ch

Report METAS-report 154.1-2020-5218-1016

This report is available in PDF format at the following link: http://www.metas.ch/nisv
(➡ Technische Berichte / Rapports techniques/ Rapporti tecnici)

Bern-Wabern, 18 February 2020
Version 2.1: 20 April 2020; changes from version 2.0 are made visible (track change mode)

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1 Introduction

1.1 The Ordinance relating to Protection from Non-Ionising Radiation

The "Ordinance relating to Protection from Non-Ionising Radiation" (ONIR) [1] published in 1999 (in its version of the 1st of June 2019), defines

- **Exposure limit values** for electromagnetic fields for frequencies ranging from 0 Hz to 300 GHz (based on ICNIRP [2]).

- The so called **"installation limit values"** that are more stringent than the exposure limit values. These limit values have been introduced as precautionary limitation of emissions. They apply to the radiation emitted by one installation in its **reference-operating mode,** which corresponds (in case of mobile telecommunication systems) to the operation at maximum "speech and data" traffic and at maximum transmission power. They have to be respected at places of sensitive use, e.g. apartments, offices, schools, children's playgrounds etc.

In other words, compliance assessment of a mobile phone base station includes a measurement of the electric field strength at a defined time as well as an **extrapolation of the measured values to the reference-operating mode**.

1.2 Measurement recommendations

As a consequence of the definitions described above, to assess the conformity of an installation with the legal requirements, a measurement of the electric field strength and additional calculations are needed. These two steps make it possible to determine the field strengths that are expected in the reference-operating mode. In order to harmonize the way these measurements and extrapolations are performed, a series of technology specific "measurement recommendations" or technical reports have already been published: GSM [3], EDGE [4], UMTS [5], Broadcasting [6], and LTE [7].

1.3 Motivation and scope of this document

With the introduction of New Radio (NR) as a technology in the 5G mobile telecommunication networks, it is necessary to develop a reference method for measuring field levels of NR installations in indoor and outdoor environments. The method should be:

- robust and practicable,
- providing extrapolations that are accurate, avoiding over- or underestimation of the electric field strength in the reference operating mode,
- taking into account the beam steering features of the 5G technology,
- taking into account the variability of the transmission direction and antenna pattern from adaptive antennas according to annex 1, paragraph 63 of the ONIR [1], as of 1st of June 2019,
- in line with the previous measurement recommendations,
- applicable to FDD as well as to TDD duplexing modes.

1.4 Outline

As in the case of the previous measurement recommendations, two different methods are proposed here:

- The code-selective method allows the compliance assessment of an installation with the installation limit value and is considered as the **reference method**.
- The spectral method (frequency selective method) does not allow the distinction of two different cells of the same operator/installation. Moreover, it suffers from overestimation of the extrapolated field strength of the reference-operating mode. While it is

able to demonstrate compliance of an installation with the regulation, it fails to make a final assessment on the non-compliance (even if the extrapolated field strength exceeds the installation limit value). This method is therefore considered as **an approximate method** (“Orientierende Messung”).

1.5 Scope

According to release 15 of the 5G-release 15 standard [8], the NR technology covers two frequency ranges: the first frequency range from 450 MHz to 6 GHz, and the second frequency range from 24.5 GHz to 52.6 GHz. The present report is **restricted to the first frequency range** up to 6 GHz.

1.6 Application and outlook

This document includes a statistical extrapolation (reduction) for adaptive antennas that has for the moment a conservative default value of 1. The precise value has to be defined in an execution recommendation to the ONIR [1].
This document can be applied for compliance tests of NR base stations with respect to the ONIR, until a new version or an official measurement recommendation of the Federal Institute of Metrology (METAS) and the Federal Office for the Environment (FOEN) is published.

2 Code-selective measurement method

2.1 Measurand

The measurement method is based on the determination of the radiated field produced by the Secondary Synchronization Signal (SSS) of the downlink of the Physical Broadcast Channel (PBCH). The identification of the SS/PBCH beam identity (SS/PBCH block index) is required. The SSS is part of the SS/PBCH blocks which are distributed over a bandwidth of 3.6 MHz up to 7.2 MHz (for carrier frequency up to 6 GHz) within the NR downlink signal (see Annex A). The SSS occupies a bandwidth of 1.905 MHz or 3.810 MHz (127 resource elements). The SS/PBCH block is in general not centered with the downlink carrier frequency. Each SS/PBCH block occupies a set of four consecutive OFDM symbols. The SS/PBCH block contains the Demodulation Reference Signal (DM-RS). The DM-RS resource elements of the SS/PBCH block carry information on the cell identity number (0 to 1007) as well as on the SS/PBCH beam identity (SS/PBCH block index) [9]. Measurement of the SSS, as well as decoding of the DM-RS signal, requires a code-selective field probe, a measuring receiver or a spectrum analyzer capable of decoding NR signals and of quantifying their power.

The bandwidth of the measuring instrumentation to quantify the SSS is not specified, but must at least cover the total SSS downlink signal bandwidth. The SSS signal bandwidth is $127 \cdot \Delta f$, whereas the SS/PBCH block has a bandwidth of $240 \cdot \Delta f$ where Δf is the subcarrier spacing of the PBCH block. According to NR numerology, the subcarrier spacing can be 15 kHz, 30 kHz, and 60 kHz for carrier frequencies up to 6 GHz. The subcarrier spacings of 120 kHz and 240 kHz are intended for carrier frequencies above 24 GHz according to [8], and they are therefore not further considered in this document. For carrier frequencies up to 6 GHz, the possible subcarrier spacings Δf for the PBCH are only 15 kHz and 30 kHz according to [10] (60 kHz is not used for PBCH). Different numerologies (subcarrier spacing) might be multiplexed within the same OFDM symbol as mentioned in [8].

In a given location, the measurement is performed as follows: for each NR cell i, all measurable SS/PBCH blocks must be identified in terms of their cell number i and SS/PBCH block index j (obtained by demodulating the DM-RS signal). Each SS/PBCH block with index j corresponds to a PBCH antenna beam. For each SS/PBCH block (identified by its index j), the electric field strength $E_{i,j}^{\mathrm{SSS(RE)}}$ per resource element of the SSS is measured. The electric field strengths $E_{i,j}^{\mathrm{SSS(RE)}}$ of all SS/PBCH blocks within a half frame are then added quadratically to build a new value. The spatial maximum $E_{i,\max}^{\mathrm{SSS(RE)}}$ of this value has to be found within the measurement volume. According to [10], all SS/PBCH blocks are transmitted within the same half frame (see Annex A.2), and one might assume [10] that this half frame is transmitted with a periodicity of 2 frames, meaning 20 ms.

The spatial maximum is determined by scanning the receive antenna taking into account:

- Standing waves in the measurement volume
- Polarization of the measuring antenna (receive antenna)
- Orientation (azimuth and elevation) of the measuring antenna.

And the following measurement conditions apply:

- Minimum distance to walls, floor, ceiling, furniture and windows : 50 cm
- Height above the floor between 0.5 m and 1.75 m.

The receive antenna used for the measurements should be of small dimensions so that it may easily be used indoor. A calibration certificate must confirm the traceability of the receive antenna to the international system of units (SI).

2.2 Appreciation value

For each NR-cell i of the base station, the measured value the electric field strength has to be extrapolated to the reference operating mode:

$$E_{i,h} = E_{i,\max}^{\mathrm{SSS(RE)}} \cdot K_i(\varphi_i, \theta_i) \tag{1}$$

with

$$E_{i,\max}^{\mathrm{SSS(RE)}} = \max\left(\sqrt{\sum_j \left(E_{i,j}^{\mathrm{SSS(RE)}}\right)^2}\right) \tag{2}$$

$$K_i(\varphi_i, \theta_i) = K_i^{\mathrm{SSS(RE)}} \cdot K_i^{\mathrm{antenna}}(\varphi_i, \theta_i) \cdot K_i^{\mathrm{stat}} \cdot K^{\mathrm{duplex}} \tag{3}$$

The variables are defined as

$E_{i,h}$	Extrapolated value of the electric field strength for cell i in V/m.
$E_{i,\max}^{\mathrm{SSS(RE)}}$	Spatial maximum within the measurement volume of the quadratic sum of the SSS electric field strength per resource element (RE) of all SS/PBCH blocks of cell i as defined by equation (2). The sum is performed on all available SS/PBCH blocks indexes j located within the same half frame.
$E_{i,j}^{\mathrm{SSS(RE)}}$	Electric field strength (in V/m) per resource element (RE) of the SSS of cell i and SS/PBCH block index j. This value is the quadratic mean of all measured SSS resource elements within the same SS/PBCH block.
$K_i(\varphi_i, \theta_i)$	Global extrapolation factor for cell i. The global factor depends on the azimuth φ_i and on the elevation θ_i.
$K_i^{\mathrm{SSS(RE)}}$	SSS extrapolation factor for cell i.
$K_i^{\mathrm{antenna}}(\varphi_i, \theta_i)$	Antenna correction factor taking into account the difference between the antenna diagram of the SS/PBCH signal of cell i and the antenna diagram of the total signal in the maximum permitted operating condition. The antenna correction factor depends on the azimuth φ_i and on the elevation θ_i.
φ_i	Azimuth, defined as the horizontal angle in a spherical coordinate system, of the measurement location with respect to the transmit antenna of cell i.
θ_i	Elevation, defined as the vertical angle in a spherical coordinate system, of the measurement location with respect to the transmit antenna of cell i.
K_i^{stat}	Beam statistic factor for cell i.
K^{duplex}	Duplex factor.

Equation (1) is similar to the extrapolation of the other measuring recommendations [3,4,5,7], with the difference of the azimuth and elevation dependence. In given situations, the dependence of the azimuth and of the elevation can be neglected, thus providing a unique extrapolation factor for each cell. This is discussed further in section 4.

2.3 Comment

In contrast to LTE where the cell specific reference signals are permanently transmitted on the same antenna ports as the payload data, the NR works differently. In NR, the payload data are transmitted on the Physical Downlink Shared Channel (PDSCH) via the logical antenna ports 1000 to 1011, whereas the synchronization and identification signals are transmitted on the PBCH channels using the logical antenna port 4000. The SS/PBCH blocks can be transmitted on up to 4, or 8 (up to 6 GHz) different SS/PBCH beams.
The PDSCH channel has its own beams that are generally more focused than the SS/PBCH beams (see Figure 1). The PDSCH beam intensity depends on the payload data, and might consequently vary in time.

For the determination of the appreciation value, the electric field strength of the different SS/PBCH block indexes are combined as defined in equation (2). The motivation to combine the field strength of different SS/PBCH block indexes is first to take into account the multipath propagation of the base station radiation, and secondly to provide more realistic values of the radiation of the base station, especially in the region between two SS/PBCH beams as illustrated by Figure 1.

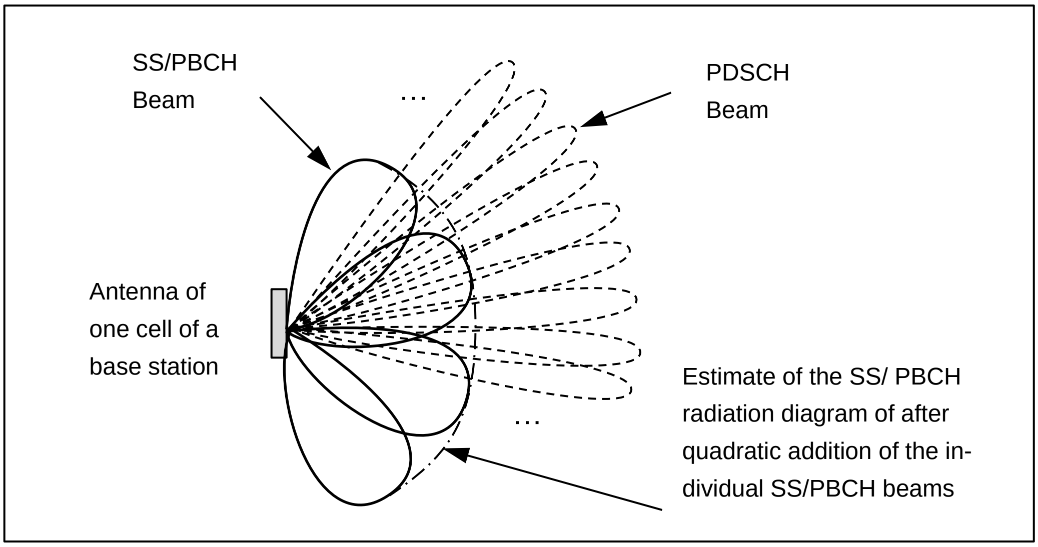

Figure 1: Schematic representation (seen from above) of the horizontal radiation pattern of a NR-base station cell. The PDSCH beams are not all represented.

3 Extrapolation factor for the SSS

For each cell i ~~and for each SS/PBCH block index j~~ of the base station, an extrapolation factor $K_i^{\mathrm{SSS(RE)}}$ is defined as:

$$K_i^{\mathrm{SSS(RE)}} = \sqrt{\frac{P_{i,\mathrm{permitted}}}{P_i^{\mathrm{SSS(RE)}}}} \qquad (4)$$

with

$K_i^{\mathrm{SSS(RE)}}$ SSS extrapolation factor for cell i.

$P_i^{\mathrm{SSS(RE)}}$ Actual effective radiated power (ERP) per resource element (RE) of the SSS of the SS/PBCH block of cell i in W. It corresponds to the maximum in all directions of the "summed SSS ERP radiation pattern" $P_i^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i)$, and it is given by the following equation:

$$P_i^{\mathrm{SSS(RE)}} = \max_{\varphi_i, \theta_i} P_i^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i) \qquad (5)$$

$P_i^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i)$. "summed SSS ERP radiation pattern" obtained by summing the ERP radiated power per resource element of all SS/PBCH beams as defined by the following equation:

$$P_i^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i) = \sum_j P_{i,j}^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i) \qquad (6)$$

$P_{i,j}^{\mathrm{SSS(RE)}}(\varphi_i, \theta_i)$ Actual "effective radiated power" per resource element in W of the SSS of the SS/PBCH block of cell i and index j in the direction given by the azimuth φ_i and by the elevation θ_i.

$P_{i,\mathrm{permitted}}$ Maximum permitted ERP in W, taking into account the signal of all antenna ports of cell i: PSDCH, PBCH, and PDCCH.

Notes

1. The maximum ERP $P_{i,\mathrm{permitted}}$ refers to the maximum permitted ERP without any reduction.
2. The permitted power $P_{i,\mathrm{permitted}}$ (according to the location datasheet) and the actual power of the reference signals $P_i^{\mathrm{SSS(RE)}}$ are provided by the network operator.
3. The actual power of the reference signals $P_i^{\mathrm{SSS(RE)}}$ is defined as the power per resource element, and not as the total power of the SS/PBCH block.

4 Antenna Correction Factor

4.1 Definition

For each cell i and for each azimuth φ_i and elevation θ_i, the corresponding extrapolation factors $K_i^{\text{antenna}}(\varphi_i,\theta_i)$ are defined as:

$$K_i^{\text{antenna}}(\varphi_i,\theta_i) =$$

$$\begin{cases} 1 & \text{if } A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) < 10 \\ & \text{ and } A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) \le A_i^{\text{total}}(\varphi_i,\theta_i) \\ A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)/A_i^{\text{total}}(\varphi_i,\theta_i) & \text{if } A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) < 10 \\ & \text{ and } A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) > A_i^{\text{total}}(\varphi_i,\theta_i) \\ K_{i,\max}^{\text{antenna}} & \text{if } A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) \ge 10 \end{cases} \tag{7}$$

with

$$A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i) = \sqrt{\frac{P_i^{\text{SSS(RE)}}}{P_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)}} \tag{8}$$

$$K_{i,\max}^{\text{antenna}} = \max_{\left\{\varphi_i,\theta_i \,|\, A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)<10\right\}} A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)/A_i^{\text{total}}(\varphi_i,\theta_i) \tag{9}$$

The variables are defined as

$K_i^{\text{antenna}}(\varphi_i,\theta_i)$	Antenna correction factor taking into account the difference between the antenna diagram of the SS/PBCH signal of cell i and the antenna diagram of the total signal in the maximum permitted operating condition. The antenna correction factor depends on the azimuth φ_i and on the elevation θ_i.
$K_{i,\max}^{\text{antenna}}$	Maximum value of the ratio $A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)/A_i^{\text{total}}(\varphi_i,\theta_i)$, where the maximum is taken on all directions for which the attenuation $A_i^{\text{SSS(RE)}}(\varphi_i,\theta_i)$ of the SS/PBCH beam is less than 10 (corresponds to 20 dB).

$A_i^{\text{SSS(RE)}}(\varphi_i, \theta_i)$	Attenuation, according to equation (8), of the "summed SSS ERP radiation pattern" of cell i in the direction given by the azimuth φ_i and by the elevation θ_i, as given by equation (6). This ratio is greater than 1, and it can sometimes be expressed in dB as $20 \cdot \log_{10}\left(A_i^{\text{SSS(RE)}}(\varphi_i, \theta_i)\right)$.
$A_i^{\text{total}}(\varphi_i, \theta_i)$	Attenuation of the total signal radiation pattern of cell i in the direction given by the azimuth φ_i and by the elevation θ_i. The total radiation pattern corresponds to the envelope of all worst case radiation patterns in the permitted operation mode. This attenuation is defined as a "voltage ratio" (in contrast to a "power ratio") greater than 1, and it can sometimes be expressed in dB as $20 \cdot \log_{10}\left(A_i^{\text{total}}(\varphi_i, \theta_i)\right)$.
$P_{i,\text{permitted}}$	Maximum permitted ERP in W, taking into account the signal of all antenna ports of cell i: PSDCH, PBCH, and PDCCH.
$P_i^{\text{SSS(RE)}}(\varphi_i, \theta_i)$	"summed SSS ERP radiation pattern" obtained by summing the ERP radiated power per resource element of all SS/PBCH beams as defined by equation (6).
$P_i^{\text{SSS(RE)}}$	Actual ERP per resource element of the SSS of the SS/PBCH block of cell i in W, as defined by the equation (5).

4.2 Comment

The antenna correction factor $K_i^{\text{antenna}}(\varphi_i, \theta_i)$ takes into account the difference between the antenna diagram of the SS/PBCH signal of cell i and the antenna diagram of the total signal.

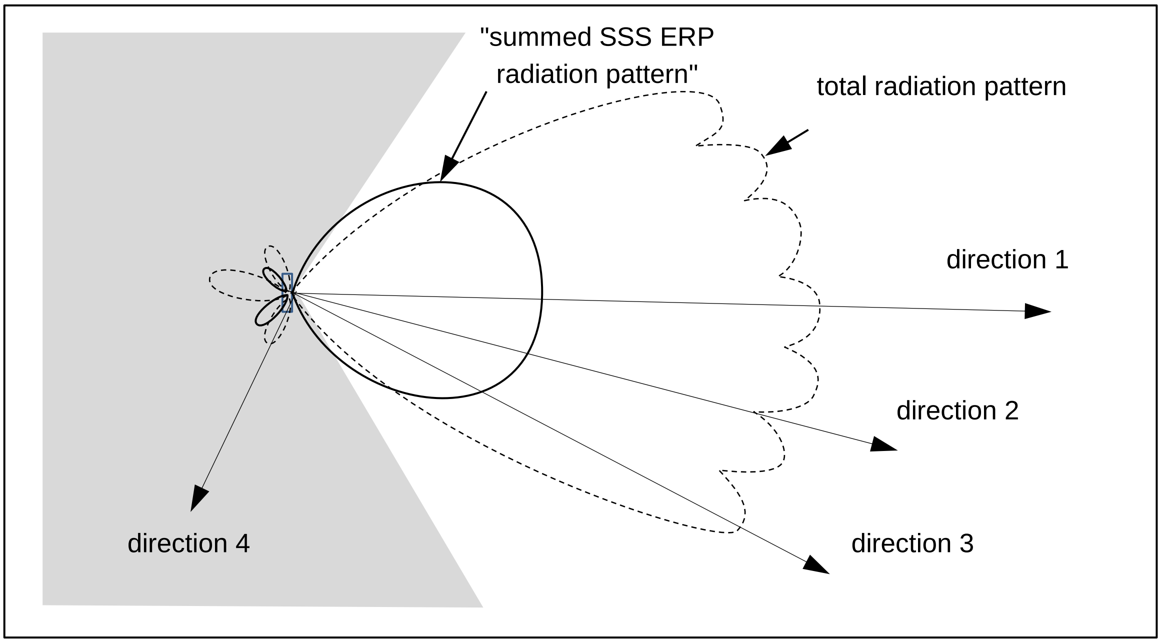

Figure 2: Schematic representation (seen from above) of the horizontal radiation pattern of a NR-base station cell.

The equation (7) can be explained using the following Figure 2:

- In direction 1, we have approximately $A_i^{\mathrm{SSS(RE)}}(\varphi_i,\theta_i) \cong 1$ (0 dB) and $A_i^{\mathrm{total}}(\varphi_i,\theta_i) \cong 1$ (0 dB). In this case, the first part of equation (7) applies: $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) = 1$.

- In direction 2, let us assume that $A_i^{\mathrm{SSS(RE)}}(\varphi_i,\theta_i) = 1$ (0 dB) and $A_i^{\mathrm{total}}(\varphi_i,\theta_i) = 1.1$ (0.83 dB). The first part of equation (7) applies: $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) = 1$. This means that no reduction factor is applied despite the fact that the total radiated beam in direction 2 is more attenuated than the SS/PBCH beam in this direction.

- In direction 3, let us assume that $A_i^{\mathrm{SSS(RE)}}(\varphi_i,\theta_i) = 1.25$ (1.94 dB) and $A_i^{\mathrm{total}}(\varphi_i,\theta_i) = 1.1$ (0.83 dB). The second part of equation (7) applies: $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) = 1.14$. This means that an extrapolation factor is applied to take into account the fact that the SS/PBCH beam in this direction is more attenuated than the total radiated beam.

- In direction 4, we are behind the transmit antenna. The radiation pattern does not totally vanish, but the radiation is small compared to radiation in the front direction. Let us assume that $A_i^{\mathrm{SSS(RE)}}(\varphi_i,\theta_i) = 25$ (27.96 dB) and $A_i^{\mathrm{total}}(\varphi_i,\theta_i) = 5.0$ (13.98 dB). In this case, the third part of equation (7) applies: $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) = K_{i,\max}^{\mathrm{antenna}}$. The value $K_{i,\max}^{\mathrm{antenna}}$ is the maximum of $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i)$ among all directions for which the SS/PBCH beam is sufficiently strong ($A_i^{\mathrm{SSS(RE)}}(\varphi_i,\theta_i) < 10$). This region is represented in white in Figure 2 whereas the region where this condition is not fulfilled is represented in light grey. Since the worst case antenna correction factor is approximately given by the direction 3, we have: $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) \cong 1.14$.

This examples is a didactic illustration the equation (7) for a horizontal cut of the antenna diagrams as represented in Figure 2. However, the equation (7) is more general and it also takes into account the elevation θ_i.

The antenna correction factors $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i)$ depend on the type of antenna and on the orientation of the antenna. These factors must be available, for example in a database or from the antenna manufacturer.

4.3 Simplifications

For practical reasons, the direction dependent antenna correction factors $K_i^{\mathrm{antenna}}(\varphi_i,\theta_i)$ can be simplified to one value $K_{i,\max}^{\mathrm{antenna}}$ as defined by equation (9). This simplification is totally acceptable to determine the appreciation value. However, it might lead to a too important overestimation of the signal from the operator point of view. In this case, different strategies are available:

- As illustrated in Figure 1, the azimuthal difference between the PDSCH beam and the SS/PBCH beam should not significant. Therefore, one might simplify the antenna correction factor as:

$$K_i^{\mathrm{antenna}}(\theta_i) = \max_{\varphi_i} K_i^{\mathrm{antenna}}(\varphi_i,\theta_i) \qquad (10)$$

  The antenna correction factor has thus only a dependence on the elevation θ_i.

- Figure 3 below illustrates a typical elevation (vertical cut) difference between the PDSCH beam and the SS/PBCH beam.