Exclusion regions for LTE base stations in heterogeneous cell structures

Bruno Pires and Luís M. Correia

Abstract—The objective of this work was to develop an exclusion region estimation model for base station antennas in heterogeneous cell structures. Two different scenarios were designed, one considering an indoor environment and another for an outdoor one. For the indoor scenario, a microstrip patch antenna was designed in CST, for the 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz frequency bands. For the outdoor scenario, a dipole array antenna was designed, operating in the same frequency bands as the indoor one. From both simulation results and the far field model, a global indoor model and a global outdoor model were developed, allowing the estimation of the electric field as a function of distance, considering the direction of maximum radiation; the cylindrical exclusion region model is used for other propagation directions. When compared to measurement results, the developed models result in an overestimation 180% for 800 MHz, 335% for 900 MHz, and 676% for 2100 MHz in the region closer to the antennas. It is concluded that the developed model overestimates the real value of an exclusion region, always considering the worst-case perspective of exposure to electromagnetic radiation.

Index Terms—Electromagnetic field, Antenna, Exclusion Region, GSM, UMTS, LTE.

I. INTRODUCTION

The increase of mobile data traffic, mainly due to the new contents and services, is leading to the deployment of more and more Base Stations (BS) in highly populated areas. This is alerting the population to the presence of the near BS structures and generating concerns of potential health risk caused by the radiation from the mobile communication systems.

Exclusion zone is the area around a BS where the EMFs exposure guidelines may be exceeded. This areas for 2G and 3G are well studied and defined by operators in order to protect the public from potential harmful levels of radiation. In highly populated areas, where the number of BS is very high and the cell sizes tend to be smaller and heterogeneous, the addition of LTE antennas to the existing infrastructures is most likely to change the EMF behaviour and consequently the exclusion zones may vary from the ones defined for the former technologies. Therefore, there is a need to study and develop accurate models to redefine exclusion zones for the situations where LTE is to be employed.

Several models have been developed in order to estimate exclusion zones. The Far field model [1] and Far field approximation [2] are the most common estimation models that can be found in literature. These are simple models to estimate exclusion regions but in most times over-predicts the real exposure levels and have a limited applicability, since the exclusion regions are often smaller than the validity limits of the model. In [3], a model for exclusion zone of BSs located in free-space areas is presented, taking as assumption that there are no obstacles within the exclusion zone. Synthetic and gain based models are far more accurate and complex than far field models, providing near field estimation for panel antennas [4]. Hybrid models provide a prediction algorithm to evaluate the field strength distributions around BS antennas, making possible the application in different ranges: very near the antenna, near field region and far field region. Despite being the more complex model, it takes into account the surround environment of the BS and is very accurate in the regions near the antenna [5], [6]. In [7] and [8], the influence in EM of BS installation structures and the presence of penetrable objects are presented.

This work aims to develop a model to estimate exclusion regions for LTE base stations in heterogeneous cell structures. BS antennas. The radiated EMF need to be study as well as the impact in the EMF of the heterogeneity of the environment surrounding the BS, namely the infrastructure supporting the antennas.

The structure of this paper is the following: Section I - Introduction; Section II - Model Development; Section III - Result Analysis; Section IV - Conclusions.

II. MODEL DEVELOPMENT

A. Theoretical Approximation Model

In order to determine the exclusion zone around an antenna, one needs to define the models to be used in order to evaluate EMF as a function of the distance to verify compliance with the recommendations described in the previous chapter. In this section, the models to be used in the far field and near field regions of an antenna are presented.

1) Far Field Model

From [1] one can estimate the rms value of the power density $S$ in the far field region by applying the following equation:

$$S(d, \theta, \phi)[W/m^2] = \frac{P_{in}G(\theta, \phi)}{4\pi d^2}, \quad d > \frac{2D^2}{\lambda}$$

(1)
where:
- \( d \): Distance from the evaluation point;
- \( \theta, \phi \): Elevation and azimuth angles;
- \( P_{\text{in}} \): Input power of the antenna;
- \( G(\theta, \phi) \): Generalised antenna gain;
- \( D \): Largest dimension of the antenna;
- \( \lambda \): Wavelength of the electromagnetic wave;

In this region there is no need to compute the magnetic field, as the electric field is enough to obtain all the information about the EMF, whereas in the near field region one needs to compute both. This model is useful for areas in the far field region of an antenna, whereas for distances closer to the antenna, it tends to overestimate the real value of the EMF and since the exclusion regions are typically located in the near field region, there is a need to use an adequate model in this region.

2) Near Field Model for Outdoor Antennas

One should note that the field behaviour in the far field region is well known and presents a linear decrease with the distance. As the EMF in the near field region of the antenna does not have the same behaviour, there is a need to apply an adequate model to estimate and take into account the transition from one region to the other. This procedure has been presented in [9], by using the gain-based model [4] to obtain a linear estimation of the EMF as well as a definition of the field behaviour in between the far field and near field regions.

In the gain-based model, the near field of the entire antenna is approximated as the sum in amplitude and phase of the far field contributions of a shifted unit cell, providing a reasonably approximation at a distance of about two wavelengths away from the antenna, requiring short computation time:

\[
E(d, \theta, \phi) = \sum_{i=1}^{N_{\text{el}}} \frac{30P_{\text{in}}G_e(\theta_i, \phi_i)}{d_i} e^{-j(kd_i + \psi_i)} \tilde{u}(\theta_i, \phi_i)
\]  

(2)

where:
- \( E(d, \theta, \phi) \): RMS electric field;
- \( d_i, \theta_i, \phi_i \): Spherical co-ordinates centred at the \( i \)-th element of the array;
- \( N_{\text{el}} \): Number of elements of the array;
- \( P_{\text{in}}, i \): Input power of the \( i \)-th unit of the array;
- \( G_e(\theta, \phi) \): Generalised gain of the \( i \)-th element;
- \( k \): Propagation constant equal to \( \frac{2\pi}{\lambda} \);
- \( \psi_i \): Associated phase shift of the \( i \)-th element;
- \( \tilde{u}(\theta, \phi) \): Co-polar vector of the \( i \)-th element;

Regarding the phase shift, \( \psi_i \), it is related to the feeding currents of each unit of the array. Without considering the tilt angle and taking into account only the direction of maximum radiation as the perpendicular direction of the axis of the antenna, \( \theta = \frac{\pi}{2} \), the phase shift is assumed to be zero so that all antenna elements provide a positive contribution to the antenna radiation.

Typically, the collinear array antennas have 2, 4 or 8 elements, with uniform spacing between elements equal to the wavelength multiplied by a factor \( \Delta d_a = [0.45, 1] \), as the spacing is not always exactly equal to one wavelength:

\[
d_a = \Delta d_a \times \lambda
\]  

(3)

In his work, [9] defined an interpolation function, \( E_{\text{fit}}(d) \), which provide the best fit of the maximum points of \( |E(d)| \) as well as a function for the upper bound of the electric field, \( E_{\text{upper}}(d) \).

When estimating \( E_{\text{fit}}(d) \) and \( E_{\text{upper}}(d) \), the range defined for \( d \) implies that one should have the lower bound equal to the limit imposed by the model, \( d_{\text{min}} = 2\lambda \), and should not have high values for the \( d_{\text{max}} \) upper limit. Despite this last value is variable in the model, for a value around 6 m it has been proved that it can provide satisfactory results.

3) Field Model for Indoor Antennas

In this section, the field model for indoor antennas developed in [9] is going to be presented, in order to establish a ground for comparison with the model to be developed in this work.

Similarly to the outdoor, on the indoor one can have two different types of antennas: monopoles used for an omnidirectional radiation pattern and microstrip antennas for sectorial antennas.

Considering microstrip antennas, manufacturers do not usually provide all of the important parameters that are required to perform the simulations and therefore, there is the need to define and determine these parameters. According to [10] and [11], the length of the patch, \( L \), has typically a value on the order of \( \frac{\lambda}{2} \) and the value of the width, \( W \), one can apply the following theoretical expression:

\[
W = \frac{\lambda}{2} \sqrt{\frac{2}{\varepsilon_r + 1}}
\]

where \( \varepsilon_r \) is the dielectric constant of the substrate, with values between 2.2 and 12. According to [10], for multiband antennas in wireless systems, typical values for \( \varepsilon_r \) and thickness, \( h \), are 4.4 and 1.6 mm, respectively, and the thickness of the patch can be neglected.

The values of \( W \) and \( L \) vary according with the working frequency, as the resonant frequencies affect different areas of the patch, being higher for lower frequencies.

4) Electric Field Global Model

Taking into account the methods defined in the previous sections for the estimation of EMF in the far field and near field regions of an antenna in [9], is has also been defined a method for linking the two models in order to obtain an estimator of EMF continuous throughout the distance \( d \).

The continuity is achieved with an interpolation between the two models, with the interpolation points being carefully chosen for this purpose. One of the points chosen is the point that limits the validity of the far field model, \( S_{\text{far}}(d = 2\frac{\Delta d_a}{\lambda}) \), resulting in an interpolation point equal to \( P_b = 2\frac{\Delta d_a}{\lambda} \cdot S_{\text{far}}(d = 2\frac{\Delta d_a}{\lambda}) \). As for the interpolation point relating with the near field model, it had been chosen an intersection point between the electric field estimated by the gain based model \( S_{\text{near}}(d) \) and its upper bound, \( S_{\text{upper}}(d) \), resulting in the interpolation point \( P_a = (d_{\text{pa}}, S_{\text{upper}}(d = d_{\text{pa}})) \).

The defined strategy for the point \( P_a \) consists in the determination of all intersection points, giving preference the most distant points of the antenna. To do so, an auxiliary
variable has been defined, indicating which value of \( d \) is used by the model to find a point of intersection. This value is supposed to be less than the far field distance and, for the purpose of the work, a value of 4 m has been considered acceptable. For the case where the program does not find an intersection point within this range of values, the farthest point of intersection from the antenna is used.

The new interpolation function is obtained in the radiating near field region and, therefore, the interpolation polynomial function is also given by (5) with the same algorithm being used to determine new values for the coefficients \( A' \), \( B' \) and \( C' \). The expression of \( S_{\text{total}} \) of the global model is given by:

\[
S_{\text{total}} = \begin{cases} 
S_{\text{upper}}(d), & 2\lambda < d < d_{\text{pa}} \\
A'd^{-2} + B'd^{-1} + C', & d_{\text{pa}} < d < \frac{2D^2}{\lambda} 
\end{cases}
\]

with \( S_{\text{upper}}(d) = Z_0^{-1} \times E_{\text{upper}}^2(d) \).

The most important auxiliary variables used are the simulation range and the number of samples \( n_{\text{sp}} \) contained within this range. The lower bound \( (d_{\text{min}}) \) takes values of \( \lambda \) and \( 2\lambda \) for indoor and outdoor antennas, respectively, and for the outdoor antennas, the upper bound \( (d_{\text{max}}) \) should always be greater than the far field distance. The values for the electric field of the global model coincides with the estimated ones for the near field region at a distance up to \( d_{\text{pa}} \). The global model is given by the interpolation method described above when the distance has values between \( d_{\text{pa}} \) and far field distance. From the validity limit of the far-field, the electric field of the global model coincides with the far field one.

The performed approaches had in mind the worst-case perspective of EM radiation exposure, meaning the BS resources are fully utilised at the lowest frequency of the used band. The environment around the antenna has not been considered in the work presented.

5) Distance Evaluation Model

The global model presented in the previous sections, allow the estimation for the direction of maximum radiation so that the value of the front border of the exclusion zone, \( D_{\text{front}} \), can be determined. Regarding the other directions, a model considering correction factors have been described in [3] for a cylindrical exclusion zone and it’s going to be presented in this section.

Using the expression that relates the reference levels with the electric field, as a function of \( d \), one can obtain the \( D_{\text{front}} \) value:

\[
\sum_{i=400 \text{to } 300 \text{GHz}} S_i(d) \leq S_{\text{ref},i} \implies (...) \implies d \geq D_{\text{front}}
\]

where:
- \( S_i(d) \): Power density at frequency \( i \) as a function of the distance;
- \( S_{\text{ref},i} \): Power density reference level from ICNIRP guidelines at frequency \( i \).

Taking into consideration the conditions of the problem, \( d[m] \leq \frac{2|m|}{8} \) can be rewritten according to the number of carriers, number of MIMO antennas as well as the number of communication systems installed in the same site:

\[
R(d) \leq 1
\]

with:

\[
R(d) = \sum_{i=1}^{N_c} N_{c,i} \frac{S_{\text{total}}(d)}{S_{\text{ref},i}}
\]

where:
- \( N_c \): Number of communication systems installed in the site;
- \( N_{c,i} \): Carrier number of the communication system \( i \);
- \( N_{M,i} \): Number of MIMO elements of the BS in the communication system \( i \);
- \( S_{\text{total}}(d) \): Power density of the system \( i \) obtained with the global model;
- \( R(d) \): Exposure function;

In this work, a method of iteration of the value \( d \) that verifies the condition \( R(d) \leq 1 \) has been presented in order to reduce the complexity of (6), since it requires the computation of a system with three equations. Therefore, the value of \( D_{\text{front}} \) is given by the value of \( d \) that verifies \( R(d) = 1 \). As for the simulation range, \( d_{\text{min}} \) takes the value \( 2\lambda \), with \( \lambda \) being the maximum wavelength of all the systems involved in the simulation, for the outdoor scenario and equal to \( \lambda \) for the indoor scenario. As for the upper bound, \( d_{\text{max}} \) should ensure \( d_{\text{max}} > D_{\text{max}} \) for both outdoor and indoor scenarios. For the situation when \( d_{\text{max}} < D_{\text{max}} \), no conclusions can be taken regarding the exact value of the exclusion region, because of the limitations of the model.

As for the MatLab program, the main input parameters are \( N_{c,i} \), \( N_{M,i} \) in addition to the input parameters of the electric field global model. When considering a system or an antenna without the MIMO technology, \( N_{M,i} \) is equal to one. Since the model was developed mainly for the direction of maximum radiation, perpendicular to the array alignment and with the axis in the mass centre of the antenna, the values to be obtained for the other directions, will be overestimated.

The determination of the values for the back \( (D_{\text{back}}) \), bottom \( (D_{\text{bottom}}) \), top \( (D_{\text{top}}) \) and side \( (D_{\text{side}}) \) borders of the exclusion zone is made by applying the method of cylindrical exclusion zone. The normalised gains are determined as a function of the propagation direction from the analysis of the antenna radiation patterns, then being applied as correction factors (CF) to the values obtained in the direction of maximum radiation. In multiband BSs, the normalised gain used corresponds to the smallest value found in bands/antennas (value that provides more gain).

B. Antenna Modelling

In order to obtain results that allow the improvement of the theoretical models described in the previous sections, one has decided to use the CST Studio Suite to develop models of the antennas required for this work.

1) CST Antenna Design

In CST there are several Design Environments, however the only one used in this work is CST Microwave Studio once it is
the more adequate one to simulate 3D electromagnetic high frequency problems.

For the purpose of antenna modelling, there are a number of parameters that need to be defined, such as the dimensions of the antenna, the frequency band and the materials that constitute each part of the antenna. In CST, there is the possibility of defining several parameters in a parameter list and then associate the parameters with objects is the design environment, e.g. defining the physical dimensions of the antenna in the list and then create a rectangle with the dimensions defined in order to create the back of a panel antenna. After creating the physical structure of the antenna, CST allows one to define the material that constitute each part of the antenna, using for example copper or nickel.

The frequency range chosen must be as wide as possible because the solver used in the simulations is the Transient Solver [12]. This solver calculates fields’ developments in time, so, with a wide frequency band, the excitation signal will be small in time, decreasing the time of each simulation, comparing with another simulation with a narrower band.

In this work, one is going to use two different models, one for an indoor scenario using a microstrip patch antenna, and another for an outdoor scenario using a dipole array in a panel antenna. In the following sections, these models are going to be detailed.

2) Indoor Model

For an indoor environment, one has considered a typical microstrip patch antenna [10], which can be used for GSM, UMTS and LTE in the frequency bands of interest for this work. A microstrip antenna generally consists of a dielectric substrate sandwiched between a radiating patch on the top and a ground plane on the other side, being he patch generally made of conducting material, such as copper, which is going to be used in the model for this scenario.

For simplicity of analysis, the patch is generally square, rectangular, circular, triangular, and elliptical or some other common shape. In this scenario, one considers a rectangular patch, where the length \( L \) of the patch is usually in the range of \( 0.33 \lambda_0 < L < 0.5 \lambda_0 \), being \( \lambda_0 \) the free space wavelength. The patch is selected to be very thin such that \( M_t << \lambda_0 \), where \( M_t \) is the patch thickness. The height, \( h \) of the substrate is usually \( 0.003 \lambda_0 \leq h \leq 0.05 \lambda_0 \). The dielectric constant of the substrate \( \varepsilon_r \) is typically in the range \( 2.2 \leq \varepsilon_r \leq 12 \).

Microstrip patch antennas can be fed by a variety of methods. These methods can be classified into two categories- contacting and non-contacting. In the contacting method, the radiofrequency power is fed directly to the radiating patch using a connecting element such as a microstrip line. In the non-contacting scheme, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch. In the model for this work, the antenna is fed using a microstrip line, which consist on a conducting strip connected directly to the edge of the microstrip patch. The conducting strip is smaller in width as compared to the patch. This kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure.

According to [10], the design procedure starts by defining the values of the dielectric constant of the substrate, \( \varepsilon_r \), the intended resonant frequency, \( f_r \), and \( h \). The next step is the determination of the width, \( W \) of the patch, for which there is the following equation:

\[
W = \frac{c}{2 f_r \sqrt{\varepsilon_r + 1}}
\]

where \( c \) is the free space speed of light.

From the electrical point of view, the antenna looks greater than its physical dimensions, due to fringing effects, defining the effective length as well as the effective dielectric constant, \( \varepsilon_{reff} \), due to the waves that travel in the substrate and air. The value of \( \varepsilon_{reff} \) is given by:

\[
\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-1/2}
\]

with \( \frac{W}{h} > 1 \).

In order to determine the effective length of the patch, one needs to compute the extension of the length, \( \Delta L \) as a function of \( \varepsilon_{reff} \) and the width-to-height ratio, \( \frac{W}{h} \) using the following equation:

\[
\frac{\Delta L}{h} = 0.412 \left( \frac{\varepsilon_{reff} + 0.3}{\varepsilon_{reff} - 0.258} \right) \left( \frac{W}{h} + 0.264 \right) \left( \frac{W}{h} + 0.8 \right)
\]

The actual length of the patch can now be determined by solving:

\[
L = \frac{c}{2 f_r \sqrt{\varepsilon_{reff}}} - 2 \Delta L
\]

Finally, the effective length is computed using:

\[
L_{eff} = L + 2 \Delta L
\]

Once having the dimensions of the patch determined, one needs to design the microstrip line feed. Also according to [10], the typical impedance at the edge of a resonant rectangular patch ranges from 100 to 400 \( \Omega \). The radiation impedance of a patch at the edge, \( Z_a \) can be approximated as:

\[
Z_a \approx 90 \frac{\varepsilon_r}{\varepsilon_r - 1} \left( \frac{L}{W} \right)^2
\]

For the cases when the value of \( Z_a \) does not match well with a 50 \( \Omega \) standard microstrip, a transaction section should be used, with a characteristic impedance, \( Z_T \) given by:

\[
Z_T = \sqrt{50 Z_a}
\]

The design of the inside feed can be done using the following equation:

\[
R_n(y = y_0) = R_n(y = 0) \cos \left( \frac{\pi}{L} y_0 \right)^2
\]

where the recessed distance (the length cutting into the patch), \( y_0 \) can be obtained by:

\[
y_0 = \frac{L}{\pi} \cos^{-1} \left( \frac{50}{Z_T} \right)
\]

The width of the inset feed, \( W_0 \) can be obtained from the characteristic impedance of the line, \( Z_0 \) which for this work is considered to be the standard 50 \( \Omega \), using the following equation:

\[
Z_0 = \frac{120 \pi}{\sqrt{\varepsilon_r} \left[ \frac{W_0}{h} + 1.393 + 0.667 \ln \left( \frac{W_0}{h} + 1.44 \right) \right]}
\]
with \( \frac{w}{h} > 1 \) and \( Z_0 < \frac{126}{\sqrt{\pi f}} \).

One should note that the main parameters of the antenna should be chosen in order to obtain the worst case scenario in terms of EM radiation, providing a ground for comparison with the recommended values.

3) **Outdoor Model**

For an outdoor environment, a dipole array for a panel antenna has been considered. The length \( L \) and radius \( R \) of the dipole as well as the gap \( g \) in-between the dipole can be computed from \([10]\), by using the following expressions:

\[
L = 0.45\lambda  \tag{19}
\]

\[
R = 0.005\lambda  \tag{20}
\]

\[
g = 0.0224\lambda  \tag{21}
\]

The spacing between dipoles, \( d_a \), is given by:

\[
d_a = \Delta_{da} \cdot \lambda  \tag{22}
\]

where \( \Delta_{da} = \{0.45, 1\} \). Usually, the value of \( d_a \) is not provided by manufacturers in antennas datasheets, and it cannot be much larger than a wavelength. When it takes values equal to one, it can lead to values without any physical meaning, especially if the total length of all the spacing elements is larger than the real height of the antenna.

The height of the antenna array is given by:

\[
h_{ant} = (N_{el} - 1) \cdot d_a + h_{et} \tag{23}
\]

with:

\[
h_{et} = L + g
\]

where \( h_{et} \) is the height of an antenna element.

In order to design the back cover of the antenna, one has to define its dimensions and characteristics.

From the analysis of a real antenna, one has defined equations to determine all the dimensions of the cover. Thus, the width and height of the back panel are obtained from:

\[
W_c = 2L  \tag{25}
\]

\[
h_c = N_{el} \cdot d_a  \tag{26}
\]

For the top and bottom of the cover, the length can be obtained from:

\[
L_c = \frac{2\lambda}{3}  \tag{27}
\]

The dipoles are considered to be at a distance of \( \frac{\lambda}{3} \) from the back panel and the cover is made of aluminium with a thickness of 3 mm.

III. RESULT ANALYSIS

A. **Scenarios Definition**

In this section, the scenarios under analysis are presented: first, an indoor scenario where the model of a microstrip patch antenna is used, and then an outdoor scenario with the model of a dipole array. For both scenarios, the surrounding environment of the antennas as well as the simulation conditions, such as the meshing, are defined.

1) **Indoor Scenario**

In an indoor scenario, the typical installations of BS antennas are on the ceiling and on walls. The antennas are usually at a height of at least 50 cm people \([13]\).

For the purpose of this work, and taking the characteristics of indoor BS installations into account, one has considered to model a microstrip patch antenna in CST. As the physical dimensions of the antenna depend on the intended resonant frequency, different antennas were developed in this scenario, one for each frequency of interest, the antenna parameters for each frequency being computed according to the indoor model and presented in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PARAMETERS OF THE ANTENNAS IN THE INDOOR MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f ) [MHz]</td>
<td>800</td>
</tr>
<tr>
<td>( \varepsilon_r )</td>
<td>4.30</td>
</tr>
<tr>
<td>( h ) [mm]</td>
<td>4.50</td>
</tr>
<tr>
<td>( W ) [mm]</td>
<td>115.18</td>
</tr>
<tr>
<td>( \varepsilon_{eff} )</td>
<td>4.01</td>
</tr>
<tr>
<td>( \Delta L ) [mm]</td>
<td>2.09</td>
</tr>
<tr>
<td>( L ) [mm]</td>
<td>89.44</td>
</tr>
<tr>
<td>( L_{ef} ) [mm]</td>
<td>93.62</td>
</tr>
<tr>
<td>( y_0 ) [mm]</td>
<td>31.00</td>
</tr>
<tr>
<td>( W_0 ) [mm]</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Regarding the environment surrounding the antenna, as the typical cover of a microstrip antenna is made of plastic and the antenna is usually located on the ceiling or walls, it is neglected, as it poses no substantial effect into the exclusion region.

2) **Outdoor Scenario**

The most common outdoor BS installations are on rooftops and façades for urban sites and in masts for rural sites, therefore, for this scenario, one has decided to model a dipole array on a panel antenna.

For the panel antenna, one has considered a dipole array with \( N_{el} = 8 \). The value of \( \Delta_{da} \) was defined from \([10]\), as being equal to \( \lambda \). The values of all the physical dimensions of the antenna, needed for the design and taking into account the value of \( N_{el} \) and the frequency in consideration, are presented in Table II.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>PARAMETERS OF THE ANTENNAS IN THE OUTDOOR MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f ) [MHz]</td>
<td>800</td>
</tr>
<tr>
<td>( \lambda ) [m]</td>
<td>0.375</td>
</tr>
<tr>
<td>( \Delta_{da} ) [m]</td>
<td>1</td>
</tr>
<tr>
<td>( h_{et} ) [mm]</td>
<td>177.15</td>
</tr>
<tr>
<td>( d_a ) [mm]</td>
<td>0.375</td>
</tr>
<tr>
<td>( h_{ant} ) [mm]</td>
<td>2.63</td>
</tr>
<tr>
<td>( L ) [mm]</td>
<td>168.75</td>
</tr>
<tr>
<td>( g ) [mm]</td>
<td>8.40</td>
</tr>
<tr>
<td>( R ) [mm]</td>
<td>1.875</td>
</tr>
</tbody>
</table>

For the outdoor scenario, the back cover of the antenna has also been modelled, being the main parameters presented in Table III.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>DIMENSIONS OF THE BACK COVER FOR EACH CONSIDERED FREQUENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f ) [MHz]</td>
<td>800</td>
</tr>
<tr>
<td>( h_c ) [cm]</td>
<td>3.00</td>
</tr>
<tr>
<td>( W_c ) [cm]</td>
<td>33.75</td>
</tr>
<tr>
<td>( L_c ) [cm]</td>
<td>25.00</td>
</tr>
</tbody>
</table>
B. Model from Simulations

In order to design a model for the evaluation of the electric field in both indoor and outdoor scenarios, one has performed simulations to provide a ground for comparison with theoretical results obtained with the far field model.

1) Global Indoor Model

First, the indoor scenario is analysed. The far field distance values for the different frequencies considered in this scenario are presented in Table IV.

<table>
<thead>
<tr>
<th>( f [\text{MHz}] )</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{\text{ff}} [\text{cm}] )</td>
<td>45.4</td>
<td>40.3</td>
<td>19.8</td>
<td>16.8</td>
<td>13.4</td>
</tr>
</tbody>
</table>

In Fig.1, an example of the comparison between simulation results and the values obtained with the far field model is presented. The electric field values were obtained for the 800 MHz scenario, considering the direction of maximum radiation and an input reference power of 1 W.

In order to design an equation to model the behaviour of the electric field, the following border condition is required:

\[
e_{r} = \frac{1}{n} \sum_{n=1}^{10} e_{r,n},
\]

(28)

with:

\[
e_{r} \leq 10\%
\]

(29)

were:

- \( e_{r,n} \): Error measured at distance \( n \) [cm] when using the far field results instead of the simulation ones.

This equation is useful to determine the distance \( d_{c,ff} \) below which one should use the model resulting from the simulations instead of the far field one. This condition implies that the maximum acceptable error within a distance range of 10 cm is 10%. In Table V, the values of \( d_{c,ff} \) obtained for the considered frequencies are presented.

<table>
<thead>
<tr>
<th>( f [\text{MHz}] )</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{c} [\text{cm}] )</td>
<td>25</td>
<td>24</td>
<td>15</td>
<td>14</td>
<td>13</td>
</tr>
</tbody>
</table>

Taking these values into account, one has to determine equations to model the behaviour of the field for distances below \( d_{c,ff} \). In order to simplify the expression of the model, in the following, an example of the comparison between simulation results and the values obtained with the far field model is presented, considering the same values in dB.

![Fig. 2 - Comparison between far field model results and simulation results in dBV/m for the 800 MHz indoor scenario.](image)

Using these curves, one is able to design an equation to model the behaviour of the field radiated from microstrip patch antennas operating in different frequencies. The goal is to obtain an expression in the form:

\[
E(d) [\text{dBV/m}] = \sum_{n=0}^{2} \left[ C_{n}(f) \left( 20 \log \left( d_{\text{cm}} \right)^{n} \right) \right]
\]

(30)

where:

- \( C_{n}(f) \): Coefficient dependent on the working frequency;
- \( d \): Distance point of analysis;

The expressions of the curves corresponding to the simulations results, along with the coefficients for each frequency considered in this scenario, were obtained by using the trend line option for polynomial functions of Excel, allowing one to design the resulting model from the simulations given by:

\[
E(d) [\text{dBV/m}] = \left\{ C_{2}(f) \left( 20 \log \left( d_{\text{cm}} \right)^{2} \right) + C_{1}(f) \left( 20 \log \left( d_{\text{cm}} \right) \right) \right. + C_{0}(f) \}
\]

(31)

with \( d < d_{c,ff} \), and with the coefficients for the frequencies under analysis presented in Table VI.

<table>
<thead>
<tr>
<th>( f [\text{MHz}] )</th>
<th>( C_{2} )</th>
<th>( C_{1} )</th>
<th>( C_{0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>-0.051</td>
<td>1.537</td>
<td>26.363</td>
</tr>
<tr>
<td>900</td>
<td>-0.051</td>
<td>1.468</td>
<td>28.482</td>
</tr>
<tr>
<td>1800</td>
<td>-0.050</td>
<td>0.933</td>
<td>40.385</td>
</tr>
<tr>
<td>2100</td>
<td>-0.049</td>
<td>0.785</td>
<td>42.671</td>
</tr>
<tr>
<td>2600</td>
<td>-0.044</td>
<td>0.509</td>
<td>45.867</td>
</tr>
</tbody>
</table>

From both mathematical analysis and the trend line option for linear and polynomial functions of Excel, expressions for the determination of the coefficients were determined:

\[
C_{2}(f) = -0.000163 \, f_{[\text{MHz}]}A_{[\text{m}]}
\]

(32)

\[
C_{1}(f) = -0.0006 \, f_{[\text{MHz}]} + 1.9833
\]

(33)

\[
C_{0}(f) = -0.000004 \, f_{[\text{MHz}]}^{2} + 0.0235 \, f_{[\text{MHz}]} + 10.205
\]

(34)

The average error resulting from the application of the functions in the determination of the coefficients for the considered frequencies is 4% for \( C_{2}(f) \), 7% for \( C_{1}(f) \) and 2% for \( C_{0}(f) \), which are considered to be acceptable error values.
The comparison between simulation results and the ones obtained by using the indoor model from simulations for the considered frequencies result in an average error of 1% for all frequencies, which again is considered to be an acceptable error.

With these results, a global indoor model can be designed, considering the model from equations for distances below \(d_{c,i}\) and the far field one for distances higher than \(d_{c,i}\). This model is valid for microstrip patch antennas with an input power of 1 W, allowing one to determine the electric field in the direction of maximum radiation without overestimating the field values in the region closer to the antenna. The global indoor model is then, given by:

\[
\begin{align*}
E(d)_{[\text{dBV/m}]} &= \sum_{n=0}^{2} \left\{ C_n(f) \left( 20 \log(d_{[m]}^n) \right) \right\}, \quad d < d_{c,i} \\
E(d)_{[\text{dBV/m}]} &= 20 \log \left( \sqrt{30P_TG_R} \right), \quad d \geq d_{c,i}
\end{align*}
\]  

(35)

2) Global Outdoor Model

Similarly to the indoor scenario, the far field distance for the different frequencies considered in the outdoor scenario are presented in Table VII.

<table>
<thead>
<tr>
<th>(f , [\text{MHz}])</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_{ff} , [m])</td>
<td>48.00</td>
<td>42.62</td>
<td>21.38</td>
<td>18.30</td>
<td>14.72</td>
</tr>
</tbody>
</table>

In Fig. 3, an example of the comparison between the variation of the electric field with distance obtained from simulations and the one obtained with the far field model is presented. The electric field values were obtained for the 800 MHz scenario, considering the direction of maximum radiation and an input reference power of 1 W.

![Fig. 3 - Comparison between far field model results and simulation results for the 800 MHz outdoor scenario.](image)

For this scenario, one has considered a maximum acceptable error of 10% within a distance range of 1 m. The obtained results for \(d_{c,o}\) are presented in Table VIII.

<table>
<thead>
<tr>
<th>(f , [\text{MHz}])</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_{c,o} , [m])</td>
<td>26</td>
<td>25</td>
<td>13</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

Following the same approach as for the indoor scenario, using the curves expressed in dB, one is able to design an equation to model the behaviour of the field radiated from the dipole array antennas operating in different frequencies. The goal is then, to obtain an expression in the form:

\[
E(d)_{[\text{dBV/m}]} = \sum_{n=0}^{1} \left\{ C_n(f) \left( \log(d_{[m]}^n) \right) \right\}
\]

(38)

where:

- \(C_n(f)\): Coefficient dependent on the working frequency;
- \(d\): Distance point of analysis;
- \(\log\): Logarithmic function.

The expressions of the curves corresponding to the simulation results, along with the coefficients for each frequency considered in this scenario were obtained by using the trend line option for polynomial functions of Excel, allowing one to design the resulting model from the simulations given by:

\[
E(d)_{[\text{dBV/m}]} = \left\{ C_1(f) \log(d_{[m]}) + C_0(f) \right\},
\]

(39)

with \(d < d_{c,o}\) and with the coefficients for the frequencies in analysis presented in Table IX.

<table>
<thead>
<tr>
<th>(f , [\text{MHz}])</th>
<th>(C_1)</th>
<th>(C_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>-13.081</td>
<td>29.934</td>
</tr>
<tr>
<td>900</td>
<td>-13.351</td>
<td>30.615</td>
</tr>
<tr>
<td>1800</td>
<td>-15.402</td>
<td>33.742</td>
</tr>
<tr>
<td>2100</td>
<td>-15.941</td>
<td>34.452</td>
</tr>
<tr>
<td>2600</td>
<td>-16.537</td>
<td>35.223</td>
</tr>
</tbody>
</table>

From both mathematical analysis and the trend line option for linear and polynomial functions of Excel, expressions for the determination of the coefficients were determined:

\[
C_1(f) = -0.002 f_{[\text{MHz}]} - 11.595
\]

(40)

\[
C_0(f) = -0.000001 f_{[\text{MHz}]^2} + 0.0065 f_{[\text{MHz}]} + 25.527
\]

(41)

The average error resulting from the application of the functions in the determination of the coefficients for the considered frequencies is 1% for both \(C_1(f)\) and \(C_0(f)\) and the comparison between simulation results and the ones obtained by using the indoor model from simulations for the considered frequencies results in an average error of 4% for 800 MHz and 900 MHz and 5% for the other frequencies.

With these results, a global outdoor model can be designed, considering the model from equations for distances below \(d_{c,o}\) and the far field model for distances higher than \(d_{c,o}\). The global outdoor model is then, given by:

\[
E_r = \frac{1}{n} \sum_{n=1}^{2} \varepsilon_r n
\]

(36)

with:

\[
\varepsilon_r \leq 10\%
\]

(37)

were:

- \(\varepsilon_r n\): Error measured at the distance \(n \, [m]\) when using the far field results instead of the simulation ones.
\[
E(d)_{[\text{dBV/m}]} = \begin{cases} 
\sum_{n=0}^{1} \left\{ C_n(f) \left( \log(d_{[\text{m}]}^n) \right)^2 \right\}, & d < d_{c,o} \\
20 \log \left( \frac{\sqrt{30 P_T G_T}}{d_{[\text{m}]}} \right), & d \geq d_{c,o}
\end{cases} \tag{41}
\]

This model is valid for dipole array antennas with an input power of 1 W and \( N_{el} = 8 \), allowing one to determine the electric field in the direction of maximum radiation.

C. Measurements

By performing measurements, one is able to analyse the behaviour of the electric field radiated by a real antenna and its impact on EM exposure, in order to compare with the results of the model described in the previous section. The conducted measurements were focused on public access areas in zones close to BSs. A spectrum analyser with an omnidirectional antenna was used as measuring equipment, working in a safety evaluation mode, which allows one to determine the electric field radiated from an antenna, as well as the contribution of each frequency band on the total field value measured.

The procedure followed for the measurements in this work consists of the definition of measurement points coinciding with imaginary radials around the BS antennas separated by 45°. The number of points on each radial should be enough to describe the field behaviour as a function of distance, considering distances from 0.5 m from the BS and an interval of 0.5 m between each measurement point.

For this work, one has conducted measurements in four different BS sites, characterised as presented in Table X.

<table>
<thead>
<tr>
<th>BS</th>
<th>Location</th>
<th>Scenario</th>
<th>Installed systems</th>
<th>Measurement sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>Outdoor</td>
<td>Urban</td>
<td>LTE 800, GSM 900, UMTS 2100</td>
<td>Back side of the BS on the building terrace</td>
</tr>
<tr>
<td>BS2</td>
<td>Outdoor</td>
<td>Urban</td>
<td>LTE 800, GSM 900, UMTS 2100</td>
<td></td>
</tr>
<tr>
<td>BS3</td>
<td>Outdoor</td>
<td>Urban</td>
<td>GSM 900, UMTS 2100</td>
<td></td>
</tr>
<tr>
<td>BS4</td>
<td>Outdoor</td>
<td>Urban</td>
<td>GSM 900, UMTS 2100</td>
<td></td>
</tr>
</tbody>
</table>

From the results obtained for the back side of the BS, and applying a correction factor (CF) of 20 dB [Antu12], the electric field in the front direction of the BS is determined and presented in Fig.4.

These results allow one to establish a ground for comparison with the ones obtained through the application of the developed models as well as from the theoretical ones.

D. Model Comparison

Considering the indoor scenario, in Fig.5, an example of the comparison between the electric field computed from the global indoor simulation model with the values obtained by applying the field model for indoor antennas for 800 MHz is presented.

Following the approach done in the model from simulations, the \( d_{c,i} \) values were determined for the comparison between the global indoor model from simulations and the field model for indoor antennas, being presented in Table XI.

<table>
<thead>
<tr>
<th>( f ) [MHz]</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{c,i} ) [cm]</td>
<td>16</td>
<td>15</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

The obtained results are lower than the ones obtained from the comparison with the far field model, meaning that the model for indoor antennas is valid for distances lower than the far field one. However, for distances below \( d_{c,i} \), the global indoor model from simulations should be used in order to avoid overestimating the values of the electric field.

For the outdoor scenario, the electric field global model was used in order to compare with the global outdoor model from simulations. In Fig.6, a comparison between the two models and measurements obtained for the 800 MHz frequency band in BS1 is presented.

When comparing the results obtained from the outdoor global model with the measurement data, the highest error
value, $\varepsilon_{\text{max}}$ as well as the average error, $\bar{\varepsilon}$ obtained for all the frequency bands in each BS are presented in Table XII.

### Table XII
Maximum Error Resulting from the Outdoor Global Model

<table>
<thead>
<tr>
<th>BS</th>
<th>Frequency band [MHz]</th>
<th>$\varepsilon_{\text{max}}$ [%]</th>
<th>$\bar{\varepsilon}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>171</td>
<td>32</td>
</tr>
<tr>
<td>1</td>
<td>900</td>
<td>335</td>
<td>104</td>
</tr>
<tr>
<td>1</td>
<td>2100</td>
<td>488</td>
<td>252</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>180</td>
<td>74</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>192</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>2100</td>
<td>392</td>
<td>83</td>
</tr>
<tr>
<td>3</td>
<td>900</td>
<td>162</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>2100</td>
<td>676</td>
<td>327</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>133</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>2100</td>
<td>532</td>
<td>431</td>
</tr>
</tbody>
</table>

The comparison allows one to conclude that, despite the fact the developed models being more accurate that the theoretical ones, it still overestimates the values of the electric field, with high maximum and average error values.

### E. Estimation of Exclusion Zones

In this section, one applies the models from simulations in order to estimate exclusion zones around BS antennas. The exclusion region values in the direction of maximum radiation ($D_{\text{front}}$) were obtained for both indoor and outdoor scenarios, for all the frequencies considered in this work and considering an input power of 1 W.

Regarding the other directions, the bottom ($D_{\text{bottom}}$), top ($D_{\text{top}}$) and side ($D_{\text{side}}$) borders of the exclusion zone are determined by the method of cylindrical exclusion zone model [3]. The back border of the exclusion zone is not considered, due to the fact that the indoor antennas are usually located on walls or on the ceiling. From the analysis of the antenna radiation pattern, the normalised gains are determined as a function of the propagation direction, being applied as CFs to the $D_{\text{front}}$ values. In Table XIII, the obtained border values are presented.

### Table XIII
Exclusion Zone Borders for Indor Scenario with Input Power of 1 W

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{front}}$ [cm]</td>
<td>21</td>
<td>21</td>
<td>15</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>$D_{\text{side}}$ [cm]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$D_{\text{top}}$ [cm]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$D_{\text{bottom}}$ [cm]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

For the purpose of analysing the impact of these results on the need to define physical barriers, taking into account that the typical distance from an indoor antenna to the people is around 50 cm, and that the values of the exclusion zone borders are always below that value, there is no need to define this type of barriers.

The previously presented results were obtained by considering an input power of 1 W. Following a different analysis, one has defined the condition $D_{\text{front}} \geq 20$ cm and $D_{\text{side}} \geq 10$ cm in order to determine the input power needed to fulfil this condition for each considered frequency. The obtained input power values are presented in Table XIV.

### Table XIV
Input Power That Satisfies the Condition Under Study

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power [W]</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

From these results, and taking the typical distance from indoor antennas to the public as 50 cm, one can conclude that for all the frequencies considered in this work, and for an input power in the range between 1 W and 5 W, there is no need to define physical barriers for this type of antennas. Input power in indoor environments varies between 34 dBm and 38 dBm, which leads to $D_{\text{front}} \geq 20$ cm values always lower than 50 cm.

For the outdoor scenario, the same approach have been followed. From the application of the correction factors, one has obtained the dimensions of the exclusion zones around the antennas defined in the outdoor scenario, considering an input power of 1 W. The obtained results for the $D_{\text{front}}$ border are above 1 m for all the frequencies considered and the $D_{\text{top}}$ and $D_{\text{side}}$ borders of the exclusion zone are above 0.5 m for all frequencies.

However, as the input power in outdoor environments is typically in the range between 37 dBm and 47 dBm, a study to determine the exclusion zone borders for different input powers is needed. In order to determine the lowest values of the exclusion zones for typical outdoor BS antennas, in Table XV the exclusion zone borders are presented, considering an input power of 5 W.

### Table XV
Exclusion Zone Borders for Outdoor Scenario with Input Power of 5 W

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{front}}$ [m]</td>
<td>2.5</td>
<td>2.5</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>$D_{\text{side}}$ [m]</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$D_{\text{top}}$ [m]</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>$D_{\text{bottom}}$ [m]</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

For a worst case scenario perspective, the exclusion zone borders for an input power of 50 W were determined, being presented in Table XVI.

### Table XVI
Exclusion Zone Borders for Outdoor Scenario with Input Power of 50 W

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>800</th>
<th>900</th>
<th>1800</th>
<th>2100</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{front}}$ [m]</td>
<td>14.3</td>
<td>14</td>
<td>10.1</td>
<td>9.7</td>
<td>9.9</td>
</tr>
<tr>
<td>$D_{\text{side}}$ [m]</td>
<td>4.8</td>
<td>4.8</td>
<td>3.9</td>
<td>3.9</td>
<td>4.2</td>
</tr>
<tr>
<td>$D_{\text{top}}$ [m]</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>$D_{\text{bottom}}$ [m]</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The $D_{\text{front}}$ border of the exclusion zone take values between 2.3 m and 2.5 m with an input power equal to 5 W, and between 9.7 m and 14.3 m with 50 W. These results show that operators need to perform safety evaluations when installing new antennas on outdoor BS installations, in order to ensure the safety of the public from electromagnetic radiation.

The proposed models are a practical tool to estimate exclusion zones for microstrip patch and dipole array antennas, in order to determine if any public access areas are inside the...
exclusion region. In this case, measurements can be performed to verify that the limit levels are exceeded, and if there is need to define/ redefine physical barriers in these zones.

IV. CONCLUSIONS

The objective of this work was to estimate exclusion regions from BSs in heterogeneous cell structures, and to establish design rules that simplify the estimation process.

For the purpose of this work, two scenarios were defined: an indoor scenario considering a microstrip patch antenna, and an outdoor one where an 8 element dipole array was used. For the outdoor scenario, the dimensions of the antenna, as well as the back aluminium cover, were determined by analysing a real antenna. In both scenarios, the antennas were designed in CST MWS for each frequency of interest for this work: 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz, resulting in 5 antenna models for each scenario.

In order to design a model for the electric field in the region near the antennas, one has performed simulations for both indoor and outdoor scenarios. Values of the electric field in the direction of maximum radiation, and considering an input power of 1 W, were obtained and compared with the ones from applying the far field model for distances larger than $d_{ff}$.

Measurements were also performed on four different BSs in outdoor urban scenarios, in order to verify the electric field behaviour of real BS installations that provide a ground for comparison with the developed model. The obtained $D_{\text{front}}$ values for the indoor scenario, considering 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz and an input power of 1 W, are between 21 cm for the lower frequency and 14 cm for the higher frequency, and the values of $D_{\text{side}}$, $D_{\text{top}}$ and $D_{\text{bottom}}$ are between 10 dB and 15 dB lower. As the typical installation of indoor antennas is on wall or the ceiling, the $D_{\text{back}}$ distance has not been considered. A study to determine the minimum input power that leads to $D_{\text{front}}$ equal to 20 cm and $D_{\text{side}}$ equal to 10 cm was made, resulting in an input power of 3 W for 800 MHz and 900 MHz, 4 W for 1800 MHz and 2100 MHz and 5 W for 2600 MHz. From this analysis, the highest value of $D_{\text{front}}$ was obtained for 800 MHz with an input power of 5 W, being 48 cm. From these results, and taking the typical distance from indoor antennas to the public as 50 cm, one can conclude that for all the frequencies considered in this work, and for an input power from 1 W to 5 W, there is no need to define physical barriers for this type of antennas.

Considering the outdoor scenario, the obtained $D_{\text{front}}$ values for all the considered frequencies and an input power of 1 W, range between 0.8 m for 800 MHz and 1 m for 2600 MHz, whereas for 5 W the obtained values are between 2.3 m for 2100 MHz and 2.5 m for 800 MHz, and for 50 W between 9.7 m for 2100 MHz and 14.3 m for 800 MHz. When analysing the other directions, the $D_{\text{side}}$, $D_{\text{back}}$, $D_{\text{top}}$ and $D_{\text{bottom}}$ results are between 6.3 dB and 30 dB lower. The highest obtained value of $D_{\text{side}}$ was 4.8 m, for 800 MHz with an input power of 50 W, for $D_{\text{back}}, 0.6$ m was obtained for 2600 MHz also with an input power of 50 W and for $D_{\text{top}}$ and $D_{\text{bottom}}$ a value of 0.2 m, again for 2600 MHz with an input power of 50 W. These results show that operators need to perform safety evaluations when installing new antennas on outdoor BS installations, in order to ensure public safety from electromagnetic radiation.

For future research, one suggests the simulation of other types of antennas, such as outdoor arrays of patch antennas or arrays in indoor environments. Also, it would be interesting to run simulations for scenarios considering co-location of systems in indoor and outdoor environments as well as the co-location of mobile systems and Wi-Fi in indoor ones. It would also be relevant to study the impact of the surrounding environment of the antennas, such as the infrastructure that supports the antenna or the wall and ceiling in indoor cases.

REFERENCES


