Title	**Definition of Exclusion Zones around typical Installations of Base Station Antennas**
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Summary	The aim of this document is the definition of exclusion zones around typical base station antennas installations. A classification of installation types is first presented and essential parameters are identified. A discussion around biological effects from radiation and existing recommendations on exposure levels to electromagnetic radiation is then presented. A literature overview is made, and an approach for the estimation of exclusion zones is presented.

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LIST OF ACRONYMS

ANACOM	*Autoridade Nacional de Comunicações* (regulatory authority for the communications sector in Portugal)
BS	Base Station
BSS	Base Station Subsystem
CENELEC	*Comité Européen de Normalisation Electrotechnique* (European Committee for Electrotechnical Standardisation)
EC	European Council
EU	European Union
EIRP	Equivalent Isotropic Radiated Power
EMF	Electromagnetic Field
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDTD	Finite-Difference Time-Domain
GSM	Global System for Mobile Communications
GSM1800	Global System for Mobile Communications in the 1800 MHz band
GSM900	Global System for Mobile Communications in the 900 MHz band
ICNIRP	International Commission on Non-Ionising Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IEGMP	Independent Expert Group on Mobile Phones

IR	Ionising Radiation
monIT	Electromagnetic Radiation Monitoring in Mobile Communications
NEC	Numerical Electromagnetic Code
NIR	Non-Ionising Radiation
NRPB	National Radiological Protection Board
RF	Radio Frequency
rms	Root-mean-square
Rx	Reception
SAR	Specific Absorption Rate
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
Tx	Transmission
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access
WHO	World Health Organisation

LIST OF SYMBOLS

α_{3dB}	Azimuthal 3-dB beamwidth
θ	Elevation angle
θ_{dt}	Downtilt angle
λ	Wavelength of the electromagnetic wave
ϕ	Azimuth angle
ϕ_i	Phase difference between the element feeding coefficients
ψ_i	Associated phase shift
d	Distance from the radiating element to the point of investigation
D	Largest dimension of the antenna
D_{back}	Back limit of the exclusion zone
D_{bottom}	Bottom limit of the exclusion zone
D_{front}	Front limit of the exclusion zone
D_{side}	Side limit of the exclusion zone
d_{ff}	Minimum far-field distance
D_{He}	Element radiation pattern in the horizontal plane
d_i	Distance from the i^{th} element of the array
D_{max}	Maximum distance of the cylindrical exclusion zone
d_{rnf}	Maximum reactive near-field distance

D_{top}	Top limit of the exclusion zone
D_{Ve}	Element radiation pattern in the vertical plane
E	Electric field strength
F	Frequency
f_{max}	Maximum frequency within GSM and UMTS bands
$G(\theta,\phi)$	Antenna gain relative to an isotropic antenna in the direction of the elevation and azimuth angles
G_M	Gain of the antenna (in the direction of maximum radiation)
h	Half length of the radiating elements of a collinear array
H	Magnetic field strength
l	Antenna length
N	Number of elements in the array
P_{in}	Input power of the antenna
$P_{in\,i}$	Input power to the i^{th} unit cell
S	Power density
$\hat{u}(\theta_i,\varphi_i)$	Unitary vector of the i^{th} element
Z_0	Free space wave impedance

1. INTRODUCTION

Mobile communication systems have attained an incredible worldwide success, satisfying effectively the need of users for communication, everywhere and at any anytime. Currently, in 2004, there are more than one billion GSM users spread around the world, having reached penetration rates above 80 percent in many European countries. These cellular systems, based on the deployments of Base Stations (BSs), had to be massively spread to satisfy this high demand. Increasingly, with the recent emergence of the Universal Mobile Telecommunications System (UMTS), capacity requirements, mainly, will lead to an even higher densification of BS installations in highly populated areas.

The densification of BS installations in the vicinity of residential and working areas resulted in a higher generalised concern related with possible risks of human exposure to electromagnetic fields radiated by BS antennas. Based on several studies, the International Commission on Non-Ionising Radiation Protection (ICNIRP) has identified safety thresholds for human exposure to electromagnetic fields (EMFs) [ICNI98], which have been adopted worldwide. The European Council Union issued as well a recommendation relatively to the limitation of public exposure to EMFs [EuUn99] based on ICNIRP's guidelines, which was adopted in Portugal [MiES00]. Mobile operators have to respect these guidelines, guaranteeing that in public access areas the thresholds are respected by nearby radiating BS antennas.

One of the identified tasks of the **monIT** project (Task T2.2 of the Technical Annex [MONI04]), related to human exposure to radiation from BSs, consists of:

- elaboration of recommendations on BS installations and corresponding transmitted power;
- definition of exclusion zones in the vicinity of BSs outside which safety levels of exposure are not exceeded;
- establishment of mechanisms to restrict access to the radiating equipment and surrounding areas.

This document aims at identifying the most common BS installation types and characteristic parameters of radiating elements, as a basis to estimate exclusion zones in the vicinity of BSs, by comparison of radiation levels with the ones established in the above mentioned recommendations. Five chapters, including the present one, compose this document. In Chapter 2, a description of the most common BS installation types and corresponding characterisation is presented. Chapter 3 provides an overview on the recommended threshold values for exposure to time varying electric and magnetic fields. Chapter 4 is focused on exclusion zones; after a literature overview on electromagnetic field behaviour, modelling and estimation of exclusion zones, an approach is suggested for the estimation of exclusion zones. In Chapter 5 some conclusions are drawn. An Annex is included at the end of this report, containing a template to be issued and used when a BS survey is performed.

2. BASE STATION INSTALLATIONS

2.1 Introduction

For the deployment of a cellular network, BS antennas need to be strategically located in available places where coverage, capacity and interference conditions are balanced in the best way. The installation of a BS antenna depends on the possible conditions for mounting the antenna at the desired setting (place, height, tilt, etc.) and the surrounding environment. Despite the large heterogeneity of BS installations, it is possible to identify types of installations that group common characteristics. These are useful for the better identification of specific conditions of human exposure to EMF from these antennas.

In this chapter, an identification of BS antennas' installation configurations is presented, and the main parameters needed for the estimation of exclusion zones are identified (such as power, height, downtilt, etc.).

2.2 Classification of Installations

The most common classification of BS antennas installations is performed according to its coverage range. Since a BS has to cope with a given quality for the traffic offered inside its coverage area, low traffic density areas (rural environments) are covered by larger cells than high traffic density ones (urban environments). Three types of cells are identified:

- Large macro-cells (3-30 km) and small macro-cells (0.5-3 km): commonly used to serve either *rural* or *suburban* environments, where the density of BSs is small due to low traffic densities; antennas are typically installed on high masts, top of high buildings or other structures, using high radiated power levels to allow a wide coverage area. Propagation is typically over rooftops.
- Micro-cells (some 50-500 m): frequently used to provide coverage in *urban* areas, where requirements in terms of capacity are stringent due to high traffic demand; antennas are strategically installed (small towers, top of lower buildings or façades) radiating medium power levels in order to satisfy the capacity demand in a restricted coverage area, and to avoid interference with neighbouring cells. Propagation is

typically below rooftops.

- Pico-cell (a few tens of metres): usually used to strengthen *in-building* coverage, where demand is very high; antennas are typically placed on walls and ceilings inside buildings for the coverage of small areas, thus, requiring lower power levels.

Nevertheless, for the purpose of estimation of exclusion zones around BS antennas, the classification of BS antennas installations must be more refined, taking also into consideration the type of infrastructure supporting the antenna and the involving environment. Table 2.1 presents a classification of the most common types of BSs installations. This classification enables a more precise characterisation of each configuration.

Table 2.1 – Classification of BS installations types.

Denomination	**Cell type**	**Environment**	**Installation type**
Rtower	Macro-cell	Rural, Suburban	Tower, Mast, Water sump, “Tree”
Uroof	Micro/Macro-cell *	Urban	Roof-top
Utower			Tower
Ufaçade	Micro-cell		Building façade
Upole			Light pole or other
Iceil	Pico-cell	In-building	Ceiling
Iwall			Walls

**: The cell type will depend on the coverage area.*

A brief description of each BS installation type is presented in the next sections. It must be noted that, depending on the coverage and capacity objectives or on the specific topology of the site surrounding area, there might be configurations resulting from a combination of more than one installation type (*e.g.*, Uroof and Ufaçade). The sharing of existing sites and infrastructures (buildings, masts or other structures) is increasingly used for practical (operators have nowadays difficulties in finding new available sites) and environmental reasons (in order to minimise the visual impact). When sharing of structures is envisaged for the installation of BS antennas of different operators, the cumulative impact of the collocation of radiating equipment must be considered.

2.3 BS Installations Types

2.3.1 Rtower Type: Tower, Mast, Water sump and “Tree” in rural or suburban environments

Rtower installations on towers or masts, as illustrated in Figure 2.1, are frequently used for macro-cells in *rural* and *suburban* scenarios, where the density of BSs is low and there are often no constraints in terms of space; it is common to see mobile communications antennas some 20 to 35 m above ground level, aiming at reaching wider coverage areas. There are usually low capacity requirement in these types of scenarios, the coverage area being the most critical planning issue.

(a) Tower.

(b) Mast.

Figure 2.1 – BS antennas mounted on a tower or mast in a rural or suburban environment.

In order to minimise the visual impact of antennas on towers or masts, which considerably influences the environment, it is also common to install the telecommunications equipment on existing structures, like water sumps, Figure 2.2 (a). As this infrastructure already exists, using it to install mobile communications antennas avoids further visual intrusion in that area, and leads to a less expensive installation.

Another commonly used method to reduce intrusion of BSs in the landscape is the use of disguised infrastructures, namely simulating trees (palms, pines, or others), Figure 2.2 (b).

(a) Water sump. (b) Pine tree.

Figure 2.2 – BS antennas mounted on other infrastructures in a rural or suburban environment.

From the propagation point of view, all these four types of installations are similar: small contributions are to be expected from reflection at the surrounding areas, as there are few scattering objects surrounding the antennas in *rural* or *suburban* areas.

2.3.2 Uroof Type: Roof-top in urban environments

In typical *urban* environments, characterised by higher traffic demands, BSs need to be located closer to each other. These BSs are characterised by smaller coverage areas and lower transmitted power values (mainly micro-cells), in order to cope with these traffic requirements and avoid interference.

Installation of antennas on roof-tops is very common in *urban* environments, Figure 2.3. Scattering effects on the neighbourhood of roof-top installed antennas cannot be disregarded.

Figure 2.3 – BS antennas on a roof-top in an urban environment.

If BS antennas are positioned on the top of a building that is higher than the surrounding ones, both reflection and diffraction propagation effects ought to be accounted for, when performing a propagation study of this antenna installation type. If, on the contrary, the antennas height does not exceed the neighbouring obstacles, reflection effects are the ones that will mainly affect the signal strength. Thus, the topology of the surrounding objects will influence significantly the electromagnetic fields in the vicinity of the antenna.

2.3.3 Utower Type: Tower in urban environments

In *urban* environments, towers may as well be used for the installation of mobile communications antennas. Nevertheless, it becomes sometimes difficult to find, in this type of environment, enough physical space to house the whole BS equipment. An example of an urban tower is presented in Figure 2.4.

From the propagation point of view, it is important to consider the topology of any surrounding construction or other obstacles. Similar to the previous BS installation types, the signal strength at the vicinity of the radiating elements is effectively dependent on its height, orientation and tilt, as well as surrounding topology, hence, it being important to consider the resulting signal reflections and diffraction effects.

Figure 2.4 – BS antennas on a tower in an urban environment.

2.3.4 Upole Type: Light pole or other in urban environments

Light poles are as well an appropriate infrastructure to install mobile communications antennas in *urban* environments; the antennas are mounted on the existing light supports, Figure 2.5.

Figure 2.5 – BS antennas on a light pole in an urban environment.

The propagation phenomena that affect this type of installation depend again on the surrounding environment; if scattering objects are some tens of meters apart from the antennas, signal strength may be fairly estimated by using free space propagation equations; on the other hand, if there are obstacles close to the radiating elements, reflections need to be considered.

2.3.5 Ufaçade Type: Building façade in urban environments

Building façades are frequently used to install mobile communication antennas in residential and business areas, in *urban* environments. As the interference among neighbouring BSs might be considerably reduced by decreasing the height at which the antennas are installed, it becomes crucial to select lower points of installation, building façades being the most commonly adopted solutions, Figure 2.6.

The electromagnetic fields due to BS antennas mounted on façades are directly influenced by the buildings on which the antennas are mounted. The radiated power is mainly oriented towards streets, as outdoor coverage is intended; the signal strength inside these buildings depends on the construction type and materials used. As in the previous BS installation type, obstacles in the BS antenna vicinity, *i.e.*, either existing constructions or any other moving objects, affect the signal propagation, leading to non negligible oscillations on the received signal level due to reflections.

Figure 2.6 – BS antennas on a building façade in an urban environment.

2.3.6 Iceil Type: Ceiling in-building

Inside buildings, both in residential and business areas, the use of mobile phones becomes more and more a basic need; but, at the same time, if outdoor BSs transmit at lower signal levels, and considering the additional attenuation due to building penetration, the signal strength becomes often insufficient to establish connections inside buildings. In localised areas of high mobile usage, or where the larger sites fail to provide adequate coverage, it is common to install indoor BSs, *e.g.*, in underground parkings, shopping centres, airport lobbies, etc.. Figure 2.7 presents an example of an in-building ceiling installation in an underground parking.

Figure 2.7 – BS antenna on a ceiling in an in-building environment.

The geometry of spaces where indoor BSs ought to provide coverage, as well as the obstacles found inside, need to be considered when a propagation study of this type of environment is to be performed. Important signal reflections may be expected when the number of obstacles is not negligible, or when they are rather close to any of the radiating elements.

2.3.7 Iwall Type: Walls in-building

In today's business world, people need to be mobile throughout the company, business areas, etc.. By installing in-building wall-mounted antennas, everybody inside a building or business area is enabled to communicate from everywhere through the mobile network. Figure 2.8 is an example of this installation type.

Figure 2.8 – BS antenna wall-mounted in an in-building environment.

From the propagation point of view, this type of installation may be characterised by a combination of the effects described in the previous one, Iceil, and the one that considers BSs mounted on building façades, Ufaçade. The surrounding geometry is extremely important to be accounted for, as well as the materials used on the construction; the main circulation areas may not be disregarded, as scattering from people or vehicles may also induce a signal variation.

2.4 Parameters for Characterisation of BS Antennas Installations

BSs may be characterised through a vast set of parameters, enabling their adequate configuration for each particular location. For the current analysis, only a specific set of parameters will be depicted and described hereafter:

- Site topology:
  - Environment (rural, sub-urban, urban);
  - Installation type (Table 2.1);
  - Antenna height relatively to access areas (for a mast installation it will be the height from the ground, for a rooftop installation it will be the height to the roof top);

    - Surrounding objects (in the case of existence of, *e.g.*, buildings around the BS):
        - Topology;
        - Distance;
        - Material (concrete, metal or good reflector);
    - Proximity to so-called sensitive areas;
- System (GSM or UMTS);
- Number of carriers per BS;
- Number of transmitting (Tx) and receiving (Rx) antennas;
- Antenna:
    - Type (omni-directional or sectorial);
    - Number of elements;
    - Dimensions;
    - Radiation pattern (vertical and horizontal patterns);
    - 3dB beam width (vertical and horizontal);
    - Tilt (electrical and mechanical);
    - Feeding power per carrier.

The site topology is a fundamental issue on the estimation of BS exclusion zones. It is important to identify clearly the BS environment, the installation type, the height at which the antennas are positioned in the infrastructure, and the obstacles close to the antennas. The distance between antennas and public circulation areas or other sensitive places, together with the antenna characteristics, will influence considerably the estimation of the referred exclusion zones.

The present analysis is focused on GSM and UMTS. These two systems are based on different technologies, Time Division Multiple Access (TDMA) and Wideband Code Division Multiple Access (WCDMA) respectively. Transmission over these systems makes use of different frequency bands [890, 915] and [935, 960] MHz for GSM900, [1710, 1785] and [1805, 1880] MHz for GSM1800, [1920, 1980] and [2110, 2170] MHz for UMTS-Frequency Division Duplex (FDD) mode and [1900, 1920] and [2010, 2025] MHz for UMTS-Time Division

Duplex (TDD) mode), and bandwidths (200 kHz and 5 MHz respectively).

In Portugal, there are 40 carriers in the 900 MHz band and another 40 in the 1800 MHz one allocated to each GSM operator. In dense populated areas, this results typically in a maximum of 14 carriers per cell (6 for GSM900 and 8 for GSM1800), the transmitted power per cell resulting from the number of active carriers. Concerning UMTS, each operator owns 4 FDD carriers and 1 TDD carrier, which can be reused in every cell, subject to controlling the interference between each other.

The number of active carriers will determine the maximum transmitted power per cell. Co-location of GSM900, GSM1800 and/or UMTS antennas implies that individual contributions from each transmitter need to be accounted for, when estimating the global electromagnetic field in a certain location. Standard GSM BS transmitter maximum output levels, measured at the input of the Base Station Subsystem (BSS) Tx combiner, are presented in Table 2.2. Standard UMTS BS transmitter maximum output levels, measured as well at the input of the BSS Tx combiner, are presented in Table 2.3.

Table 2.2 – GSM BS maximum output power levels [ETSI92].

TRX power class	**GSM BS maximum output power levels [dBm]**			
	900	**1800**	**900 (micro[1])**	**1800 (micro[1])**
1	[55,58]	[43,46]	]19,24]	]27,32]
2	[52,55[	[40,43[	]14,19]	]22,27]
3	[49,52[	[37,40[	]9,14]	]17,22]
4	[46,49[	[34,37[		
5	[43,46[			
6	[40,43[			
7	[37,40[			
8	[34,37[			

Table 2.3 – UMTS BSs Equivalent Isotropic Radiated Power (EIRP) [Bena99].

UMTS BSs EIRP [dBm]

[1] Micro-BS maximum output power per carrier.

Macro	Micro
[40,43]	[30,33]

It has to be noted that the BS settings allows the output power to be reduced from its maximum level in static radio frequency (RF) power steps, in order to enable the adjustment of the coverage by the operator. In addition to this, downlink RF power control through additional power levels is almost always implemented, meaning that the maximum values presented in Table 2.2 and Table 2.3 are not often attained. In fact, when BSs are installed close to other ones, the transmitted power needs to be reduced in order to avoid interference. On the other hand, typical BSs in rural areas, located apart from neighbouring BSs, are usually operating at higher power levels. Nevertheless, for the present study, the maximum values, corresponding to the worst case, will be considered.

A BS may be either sectorised (up to six sectors, but typically three) or not. Each sector will constitute a cell, requiring one Tx/Rx antenna or even two in the reception (in case of diversity in the reception) per system (GSM900, GSM1800 or UMTS). This means that up to three Tx/Rx co-located antennas may be transmitting into a certain direction. If, in addition, more than one operator is sharing the site, even more antennas may be found in the same infrastructure.

The objective of the present document is to list typical BS installations and, for each installation type, to estimate the radiated electromagnetic fields through appropriate propagation models, aiming at defining the exclusion zones that surround each BS. Having this in mind, the sole aspect that requires to be studied is BS Tx.

There are three types of antennas used in mobile communications BSs: omni-directional, cardioids and sectorial. The radiation pattern of an antenna, together with the bandwidth and its feeding power range, are the key parameters that characterise it. The radiation pattern of an antenna is given by antenna manufacturers, usually providing only the vertical and horizontal planes, together with its gain and its 3 dB beamwidth; the 3D radiation pattern, if necessary, must be interpolated [PaGi98], resulting in an associated error. Antennas might be installed with a mechanical tilt, still being possible to adjust additionally its tilt electrically (electrical tilt), in order to better satisfy coverage and interference requirements. Other important parameters are the antenna dimensions, directly related to the number of elements that constitute it, essential for the estimation of the far-field minimum distance of an antenna.

As mentioned earlier, antennas can be located on poles, towers, shared masts, buildings, “trees” and other existing structures (*e.g.*, electricity pylons). The radiation pattern of an antenna might suffer a significant distortion due to its supporting infrastructure, which is difficult to obtain analytically.

There are many other parameters that characterise antennas and BSs; nevertheless, as these are not relevant for the present study, they are not listed here.

In order to estimate the exclusion zones of a BS, it is important to gather the essential parameter values listed above during its survey. In the Annex to this document, these are put together in a form, based on [OlCa02], to allow a systematic approach.

3. RECOMMENDATIONS ON EMF

3.1 Introduction

The densification of BS installations in the vicinity of residential and working areas resulted on a higher generalised concern related with possible risks of human exposure to EMFs radiated by BS antennas. In this chapter, a discussion on biological effects of EMFs is presented. Based on several studies, ICNIRP has identified safety thresholds for human exposure to EMFs [ICNI98] that are also presented in the current chapter. These have been adopted worldwide under recommendation by several international and national institutions, even though some countries decided to define their own thresholds on a national level (*e.g.*, Japan and Italy). Mobile operators have to respect these guidelines, guaranteeing that in public access areas the thresholds are observed by nearby radiating BS antennas.

Two different radiation sources may be considered in mobile communication systems: BS antennas and mobile terminals. However, human exposure to BSs radiation results from an involuntary act. The aim of the **monIT** project is to provide the public with general information on existing levels of public exposure to EMFs compared to recommended thresholds, focusing on the radiation of GSM and UMTS BSs.

3.2 Biological Effects of EMF

EMFs occur naturally in the Universe, having always been present on Earth. The Sun is the most intense source of EMFs we are exposed to. Other sources are antennas, power lines and electrical equipment. The RF part of the electromagnetic spectrum ranges from 3 kHz to 300 GHz. Main applications are radio and TV broadcasting, mobile communication systems, radars, microwave ovens, or even medical applications. In particular, GSM and UMTS use frequencies ranging between 890 and 2170 MHz.

The massive proliferation of mobile communications BS antennas caused a concern in the population about potential negative EMFs effects on health. Effects of EMFs on humans are a very sensitive subject, as there are still uncertainties due to lack of trustful medical information and reports on certain radiation effects. A biological effect is a measurable answer of the organism to a stimulus or a change in the involving ambient.

Two types of radiations exist: Ionising (IR) and Non-Ionising Radiation (NIR). The mechanisms of interaction of each type of radiation with the human body are very different and are shortly described next.

IR is a process by which an atom or a molecule looses an electron due to interaction of an EMF source of high levels of energy, *i.e.*, interaction with high frequency radiation above 2.4 THz. It is essential to understand that RF, with a frequency range of 30 kHz to 300 GHz, is not IR. X-rays and gamma radiation are examples of IR. This kind of radiation may produce molecular changes resulting in the damage of biological tissue, causing inclusively genetic effects.

For NIR such as RF, possible biological effects are thermal and non-thermal ones. Thermal effects are well known and quantifiable: they consist in the heating of the biological tissue. When the level of heating exceeds the natural capacity of thermo-regulation of the human organism, damage may occur, because of the body's inability to cope with or dissipate the excessive heat that could be generated. Nevertheless, since the relation between the quantity of RF energy absorbed by the different parts of the body and the corresponding elevation of temperature is well known, the establishment of safety levels of exposure to RF is possible. Non-thermal effects are still under study. The occurrence of long-term biological effects is also an open issue still to find an answer to.

In 2001, ICNIRP’s Standing Committee on Epidemiology published a major Review of the Epidemiological Literature on EMF and Health [ICNI01]. It was referred that, in the absence of experimental evidence and given the methodological uncertainties in the epidemiologic literature, there was no chronic disease for which an etiological relation to EMF could be regarded as established. In 2004, at the ICNIRP workshop [ICNI04] an overview of new studies was presented. There have been numerous epidemiological studies conducted that attempt to correlate incidence of disturbance on the sleeping cycle, tumours or cancer with RF radiations. In-vitro laboratory research could not find any consistent evidence of cancer initiating, or promotion activity of non-thermal levels of EMF at mobile RF frequencies. No evidence was found also for changes in animal reproduction, behaviour, in blood barrier permeability or other physiological parameters. In terms of human brain activity, no consistent effect of mobile terminal signals was found, during sleep or awake states, cognitive functions or cardiovascular performance, through electro-encephalography. As a conclusion, no study evidencing effects of EMF has been made in conditions to be replicated. Nevertheless, a large effort is still being done within the scientific community to clarify all these issues.

3.3 Recommended Threshold Values

Safety levels emerge as an answer to the question: when are biological effects caused by absorption of radiation harmful to human health? In this way, safety levels establish maximum allowed values for the levels of radiation exposure of the human body. Accompanying the current scientific knowledge, the establishment of safety levels are based on the search of the minimum values above which biological effects noxious to health emerge, independently of the mechanism that generates it. The only mechanism that, nowadays, is confirmed as potential generator of noxious effects resulting from exposure to RF is the thermal effect of biological tissue heating. In this way, it is based on this mechanism that the safety levels are established for the RF band.

To characterise the radiation absorbed by the body, the parameter used for the RF spectrum is the Specific Absorption Rate (SAR), which corresponds to the power absorbed by an incremental mass contained in a volume element of a given mass density. SAR represents, thus, the rate at which electromagnetic energy is absorbed by unit of tissue mass. The unit of SAR is Watt per kilogram of exposed tissue [W/kg]. Safety levels are established for the SAR parameter. Nevertheless, this parameter is difficult to measure, since it must be obtained inside the body. Given this, thresholds are also established for other electromagnetic quantities, such as power density, electric and magnetic field intensities, easily measured outside the body. These levels are designated as reference thresholds.

Reference thresholds are divided in two types of exposure: occupational exposure, corresponding to adults that are generally exposed under known conditions, trained to be aware of potential risk and to take appropriate precautions, and exposure of the general public, corresponding to individuals of all ages and of varying health status, including sensitive groups (*e.g.*, children or elderly people). Several international bodies (such as ICNIRP, IEEE, NCRP, etc.) have established safety levels based on a number of studies. Several countries adopted these levels, regulatory authorities existing in order to verify if these thresholds are respected.

In April 1998, ICNIRP published guidelines for limiting exposure to time-varying EMFs in the frequency range up to 300 GHz [ICNI98]. ICNIRP is a well known international organisation, composed of biologists, physicians and engineers, with a long and valuable experience on the radioprotection domain, being independent from industry and working in straight collaboration with World Health Organisation (WHO). These guidelines have been adopted worldwide. Reference thresholds are presented for EMFs in Figure 3.1 (for the RF part of the electromagnetic spectrum). These established reference thresholds include several safety margins, since there are still open issue related to biological effects that may be adverse to health. These levels are provided for comparison with measured values.

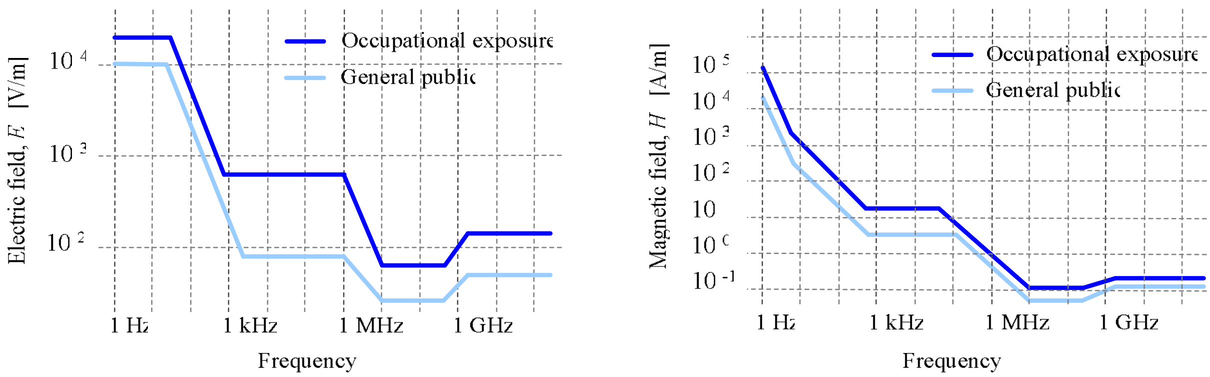


Figure 3.1 – Reference thresholds for exposure to time varying electric and magnetic fields (occupational exposure and exposure of the general public).

At the European Union (EU) level, a Council Recommendation [EuUn99] to limit the exposure of the general public to EMFs (0 Hz - 300 GHz) was adopted in July 1999, based on ICNIRP guidelines as endorsed by the Scientific Steering Committee advising the European Commission on multi-disciplinary scientific issues. The Recommendation sets a system of basic restrictions and reference levels for overall public exposure.

IEEE issued as well a recommendation [IEEE99] to prevent harmful effects in human beings exposed to EMFs in the frequency range from 3 kHz to 300 GHz. It is intended to apply to exposures in controlled (*i.e.*, incurred by persons aware of the presence of EMFs), as well as uncontrolled (*i.e.*, incurred by persons without knowledge or control of their exposure to EMFs), environments.

Besides these recommendations, an independent advisory group has issued a report, [Stew00], related to BS installations, that has been largely referenced by regulatory entities of many countries. It advocates:

- A national register of BSs, putting available information about the location and operating characteristics of all BSs: the antenna height; the date that transmission started; the frequency range and signal characteristics of transmission; the transmitter power; and the maximum power output. Easy access to such information would help to reduce mistrust among the public. Furthermore, the data would be useful when applications for new BSs were being considered, and might also be of value in epidemiological investigations.

- The establishment of clearly defined physical exclusion zones around all BS antennas, which define areas within which exposure guidelines may be exceeded. A physical barrier should define each exclusion zone and a readily identifiable nationally agreed sign with a logo should be posted. This should inform the public and workers that inside the exclusion zone there might be RF radiation exceeding national guidelines.

- At national Government level, a template of planning protocols should be developed, in agreement with industry and consumers, which can be used to inform the planning process and which must be assiduously and openly followed before permission is given for the sitting of a BS.

- An independent, random, ongoing audit of all BSs should be carried out to ensure that exposure guidelines are not exceeded outside the marked exclusion zone and that the BSs comply with their agreed specifications.

- Concerning macro-cell BSs sited within or near school grounds, the beam of greatest RF intensity should not fall on any part of the school grounds or buildings without agreement from the school and parents.

- Operators should actively pursue a policy of mast sharing and roaming where practical.

The regulatory authority for the communications sector in Portugal, ANACOM, is responsible to define safety thresholds for human exposure to EMFs, as well as to verify if these thresholds are respected by all telecommunications operators. For the public in general, the European Council Recommendation limiting public exposure to EMFs (0 Hz to 300 GHz) was adopted [ANAC01], which considers as adequate the thresholds defined by ICNIRP, and includes also several of the above presented recommendations. In particular, national City Councils are asked to authorise the installation and operation of BSs, [MECO03]. Mobile operators have to respect these guidelines, guaranteeing that, in public access areas, the thresholds are respected by nearby BS antennas.

3.4 Comparison of Recommended Thresholds

In order to provide a high level of health protection against exposure to EMFs, many countries adopted basic restrictions and specific reference levels for occupational and general public exposure, and, in addition, implemented measures with respect to sources or practices that give rise to EMFs exposure, considering as well the duration of this exposure.

Some countries adopted the values listed in the recommendations mentioned in the previous section: *e.g.*, Portugal [ANAC01], Germany [BuWA96] and Switzerland[2] [CoFS99] adopted ICNIRP / EU thresholds, and Canada [MiHe99] and USA [FeCC97] adopted IEEE's. Others defined additionally their own limits, adding or removing safety margins, *e.g.*, Japan [HAPT97], Italy [MiAm98], Belgium [MASS01] and The Netherlands [CoRS97].

Figure 3.2 shows the electric field strength levels, *E*, for GSM and UMTS frequency ranges, as recommended by ICNIRP / EU and IEEE, as well as the different levels adopted by specific countries.

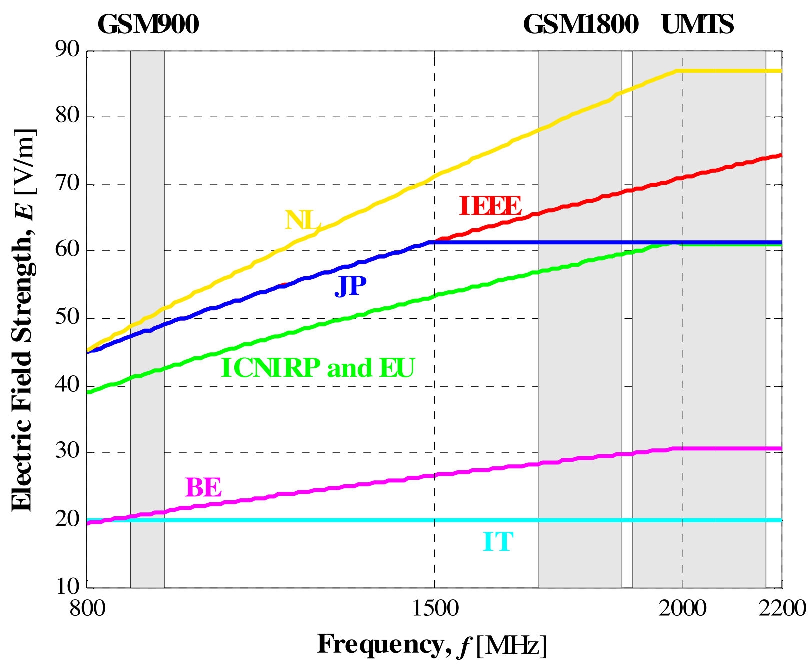


Figure 3.2 – Reference thresholds (exposure of the general public).

[2] ICNIRP values are valid generally; for sensitive areas, further safety margins are added.

4. EXCLUSION ZONES

4.1 Introduction

In Chapter 3, recommendations defining threshold values for human exposure to EMFs have been presented. Exclusion zones should be defined around radiating elements, establishing areas within which EMFs exposure guidelines are exceeded, in order to protect public in general from potential harmful levels of radiation. An example of an exclusion zone is illustrated in Figure 4.1.

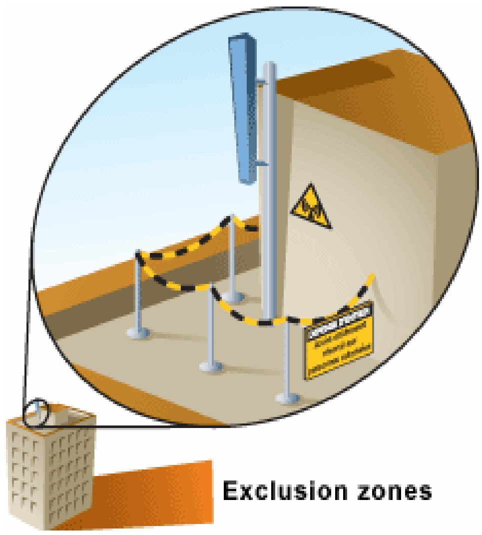


Figure 4.1 – Exclusion zone surrounding a BS antenna (extracted from [OrFr04]).

The main goal of this chapter is the estimation of exclusion zones around the typical BS installations identified in Chapter 2. BS installation characteristics and relevant parameters, identified in Chapter 2, as well as the recommended thresholds presented in Chapter 3, are essential for the estimation of exclusion zones around BSs. In addition, specific procedures are needed for the evaluation of EMFs near BSs, which represent a non-trivial issue, as it is discussed in the next sections.

4.2 Electromagnetic Field Behaviour and Modelling

EMFs around a radiating source have complex and non homogeneous behaviour characteristics. It is common to define three boundary regions [CENE02]:

- **Reactive near field region**, characterised by the coexistence of reactive and radiative energy; Electric (*E*) and Magnetic (*H*) fields have to be separately estimated to determine the power density and field impedance; it corresponds to the closest region around the transmitting antenna, delimited by:

$$d < d_{rnf}, \qquad \text{where } d_{rnf} = \frac{\lambda}{4} \tag{4.1}$$

  and:

  - d distance from the radiating element to the point of investigation, [m]
  - d_{rnf} reactive near field limit, [m]
  - λ wavelength of the electromagnetic wave, [m].

- **Radiative near field region**, also called Fresnel zone, where radiation fields dominate and where the angular field distribution depends on the distance from the antenna; *E*- and *H*-field measurements are directly interrelated by the characteristic impedance of free space. This region is delimited by:

$$d_{rnf} \le d < d_{ff}, \qquad \text{where } d_{ff} = \frac{2D^2}{\lambda} \tag{4.2}$$

  and:

  - d_{rnf} reactive near field limit, [m]
  - d distance from the radiating element to the point of investigation, [m]
  - d_{ff} far field boundary, [m]
  - D largest dimension of the antenna, [m]
  - λ wavelength of the electromagnetic wave, [m].

- **Far field region**, where the radiation pattern is independent of the distance from the transmitting antenna; *E*- and *H*-field measurements are directly related by the characteristic impedance of free space (120 π). This region corresponds to:

$$d \ge d_{ff} \tag{4.3}$$

These three boundary regions are schematically represented in Figure 4.2.

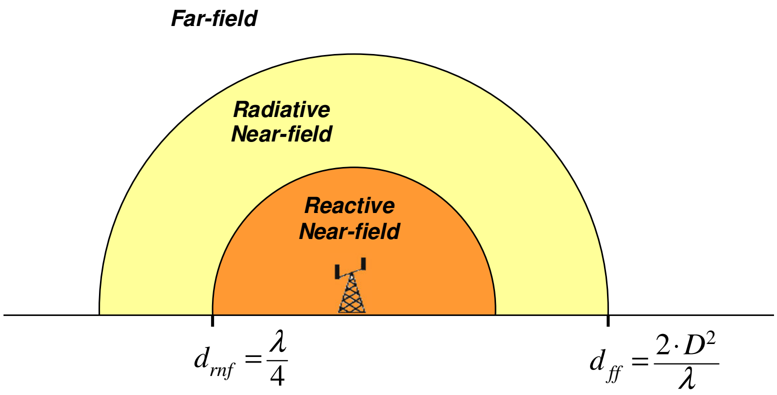


Figure 4.2 – Boundary regions of the different radiation fields existing around an antenna.

Table 4.1 presents, for the most common antenna lengths in GSM900, GSM1800 and UMTS, [KATH04], the boundary values that limit the three regions adjacent to BS antennas. The frequency used to obtain these boundaries corresponds to the worst case value (the highest frequency within each system bandwidth).

Table 4.1 – Typical boundaries for regions adjacent to BS antenna.

		GSM900		**GSM1800**		**UMTS**	
Maximum frequency	f_{max} [MHz]	960		1880		2170	
Wavelength	λ [m]	0.313		0.160		0.138	
Antenna length	D [m]	0.3	2.6	0.2	2.6	0.2	2.6
Maximum reactive near-field distance	d_{rnf} [m]	0.08		0.04		0.03	
Minimum far-field distance	d_{ff} [m]	0.6	43.2	0.5	84.5	0.6	98.0

In each of these three regions, the radiated field does not present the same behaviour and adequate propagation models are required to estimate the exact field strength at any specific distance. For the far-field zone there are well-known and simple expressions that determine the field strength. Nevertheless, as it can be seen in Table 4.1, for large dimensions of the antenna, the distance of the far-field zone is very large. As it is seen in the next sections, for typical radiated power values and antenna dimensions, the field at the minimum far-field distance is below the recommended thresholds. Refined near-field propagation models or approximations for the estimation of the exclusion zone are needed. An overview on propagation models is presented in what follows.

4.3 Survey on Propagation Models for Estimation of Exclusion Zones

4.3.1 General considerations

Typically, exclusion zones around BS antennas, inside which exposure thresholds may be exceed, are in the near-field region of the radiating antenna (some metres). These zones may be obtained either by measurements, or by prediction through complex simulations or through the application of simple models, which enable the calculation of the radiation levels in the vicinity of the BS antennas.

Measurement procedures to assess, at points of investigation, the EMF components (*E* and/or *H*) radiated by an antenna, as well as the maximum localised SAR in a phantom model that simulates a person exposed to radio frequency fields, are presented in [CENE02]. Measurements are rather time consuming and BS type dependent.

As an alternative to the measurement procedure, simulations may be run in order to obtain good estimates of radiated fields around BS antennas; this approach involves powerful equipment and requires sometimes much time to obtain precise results.

Another possible way to estimate exclusion zones around BSs is the selection of adequate models in order to obtain a good prediction of the radiation levels; as many models are rather accurate and simple to apply, it turns out to be the most practical solution. Several models are found in the literature for the estimation of EMFs in the far- and near-field regions of BS antennas. In general, these models aim at presenting simple formulations, assessed usually through rather complex simulations (especially for near-field models, as they are not as precise as far-field ones). It is also possible to find in the literature information on SAR predictions, these being dependent on body models used.

An overview on models found in the literature, which allow the prediction of EMFs radiated by an antenna or SAR estimates, is presented below.

4.3.2 Far-field model

The far-field model [CENE02] is one of the most common estimation models found in the literature. Despite of the simplicity of this model, its applicability is rather limited, as it requires the investigation point to be in the far-field region, which may correspond to some tens of metres (it depends on the antenna length, as shown in Table 4.1); if used in the near-field region, this model over-estimates the field strength.

The root-mean-square (rms) value of the power density, $S(d,\theta,\phi)$, is expressed by:

$$S\left(d,\theta,\phi\right)_{\left[\mathrm{W/m^2}\right]} = E\left(d,\theta,\phi\right)\cdot H\left(d,\theta,\phi\right) = \frac{P_{in}\cdot G\left(\theta,\phi\right)}{4\pi\cdot d^2} \quad , \quad d \geq \frac{2D^2}{\lambda} \qquad (4.4)$$

where:

- $E(d,\theta,\phi)$ rms electric field, [V/m]
- $H(d,\theta,\phi)$ rms magnetic field, [A/m]
- d distance from the radiating element to the point of investigation, [m]
- θ and ϕ elevation and azimuth angles,
- P_{in} input power of the antenna, [W]
- $G(\theta,\phi)$ antenna gain relative to an isotropic antenna in the direction of the elevation and azimuth angles, θ and ϕ.
- D largest dimension of the antenna, [m]

The rms electric field, $E(d,\theta,\phi)$, is given by:

$$E\left(d,\theta,\phi\right)_{[\mathrm{V/m}]} = \frac{\sqrt{30P_{in}G\left(\theta,\phi\right)}}{d} \quad , \qquad (4.5)$$

where:

- $E(d,\theta,\phi)$ rms electric field, [V/m]
- d distance from the radiating element to the point of investigation, [m]
- θ and ϕ elevation and azimuth angles,
- P_{in} input power of the antenna, [W]
- $G(\theta,\phi)$ antenna gain relative to an isotropic antenna in the direction of the elevation and azimuth angles, θ and ϕ.

In the far-field region, the rms magnetic field, $H(d,\theta,\phi)$, is expressed by:

$$H(d,\theta,\phi)_{[\mathrm{A/m}]} = \frac{E(d,\theta,\phi)}{Z_0} \ , \tag{4.6}$$

where:

- $H(d,\theta,\phi)$ rms magnetic field, [A/m]
- $E(d,\theta,\phi)$ rms electric field, [V/m]
- d distance from the radiating element to the point of investigation, [m]
- θ and ϕ elevation and azimuth angles,
- Z_0 free space wave impedance (equal to 120 π), [Ω]

4.3.3 Far-field approximation

In [MNMV02], the validity of simple formulas based on cylindrical and far-field approximations for calculating the distances from BS antennas to comply with safety guidelines is discussed and compared with finite-difference time-domain (FDTD) results. It is concluded that, for BS antennas, the following expressions can be used to obtain approximate results for the average value of the power density, $S(d,\theta,\phi)$, near the array:

$$S(d,\theta,\phi)_{[\mathrm{W/m^2}]} = \begin{cases} \dfrac{P_{in}}{2\cdot\alpha_{3dB}\cdot D\cdot d} & for \quad \dfrac{D^2}{4\lambda} \le d < \dfrac{\alpha_{3dB}G(\theta,\phi)D}{4\pi} \\ \dfrac{P_{in}G(\theta,\phi)}{4\pi d^2} & for \quad d \ge \dfrac{\alpha_{3dB}G(\theta,\phi)D}{4\pi} \end{cases} \tag{4.7}$$

where:

- P_{in} input power of the antenna, [W]
- α_{3dB} azimuthal 3-dB beamwidth, [rad]
- D largest dimension of the antenna, [m]
- d distance from the radiating element to the point of investigation, [m]
- λ wavelength of the electromagnetic wave, [m]
- $G(\theta,\phi)$ antenna gain relative to an isotropic antenna in the direction of the elevation and azimuth angles, θ and ϕ.
- θ and ϕ elevation and azimuth angles,

As it can be seen, the minimum distance of applicability of this model is much shorter (1/8) than the one considered by the far-field model in (4.4). It is mentioned in fact that accurate results can be obtained for BS antennas for distances above D^2/λ using the far-field expression (4.4). Anyway, at distances where the far-field approximation is not the best calculation method, it always over-predicts the real exposure levels.

4.3.4 Cylindrical exclusion zone

In [MFRL02], a practical measurement procedure is described to evaluate compliance with EC recommendation limits on EMFs exposure in the vicinity of a BS [EuUn99]. A rigorous but practical assessment procedure is presented, in order to guarantee that the thresholds on exposure are not exceeded in any accessible location within the coverage area of a BS.

It is stated that only for BSs located in free-space areas, like rural zones where obstacles are not present within the exclusion zone, a correct prediction using simple formulas can be derived. BSs in urban environments with scatterers near the exclusion zone will require additional measurements, both inside and outside the exclusion zone, to be able to ensure that the EC recommendation thresholds are not surpassed.

For BSs located in free-space areas, the power density near the antenna (collinear array of N half-wave dipoles) is, according to [MFRL02], estimated by computing the power density on the surface of an imaginary cylinder that extends from the bottom of the lowest element to the top of the highest element:

$$S(d,\theta,\phi) = \frac{P_{in} G(\theta,\phi)}{2 l \pi d}, \quad d > \frac{\lambda}{2} \tag{4.8}$$

where:

- P_{in} total radiated power by the array, estimated as being the highest power value allowed for the class type the BS belongs to, [W]
- $G(\theta,\phi)$ radiating sector panel gain,
- l antenna length, [m]
- d distance from the antenna at which estimates of power density are desired,
- λ wavelength of the electromagnetic wave, [m]

Limits for the top and bottom of the cylinder (D_{top} and D_{bottom}) are also suggested as being equal to 0.3 D_{max}, D_{max} being the maximum distance of the cylindrical exclusion zone. When a downtilt θ_{dt} is used, the following correction of these values is suggested:

$$D'_{top} = D_{top} \cos(\theta_{dt}) \qquad (4.9)$$

$$D'_{bottom} = D_{bottom} \left[1 + \sin(\theta_{dt})\right] \qquad (4.10)$$

A limit for the back, D_{back} is also estimated as being equal to 0.1 D_{max}. When the BS has several sector antennas, the total exclusion zone results from the added composition truncated sector cylinders of all the individual exclusion zones.

4.3.5 Far-field-gain-based model

The far-field-gain-based model [BiGi99] is a fast and efficient method for evaluating the EMF levels radiated by BS uniform array antennas in the near-field area. It is obtained in two steps. First, the gain of the entire antenna is derived from the combination of the far-field radiation pattern of an antenna element and the array factor; by assuming that the BS antennas are uniform arrays, a good estimate of the near-field radiated by the antenna as a combination of the far-field radiated by each element of the array can be obtained:

$$E(d,\theta,\varphi) \simeq \left| \sum_{i=1}^{N} \frac{\sqrt{30 P_{in} G_e(\theta_i,\varphi_i)}}{d_i} e^{-j\phi_i} \hat{u}(\theta_i,\varphi_i) \right|, \quad d > 3\lambda \qquad (4.11)$$

and

$$G_e(\theta_i,\varphi_i) \simeq \frac{G_M D_{Ve}(\theta) D_{He}(\varphi)}{N} \qquad (4.12)$$

$$\phi_i = (i-1)\phi + \frac{2\pi d_i}{\lambda} \qquad (4.13)$$

where:

- N number of radiating elements of the collinear array,
- (d_i, θ_i, φ_i) spherical co-ordinates centred at the i^{th} element of the array,

- P_{in} total radiated power by the array, estimated as being the highest power value allowed for the class type the BS belongs to, [W]
- $G_e(\theta_I,\varphi_i)$ radiating sector panel gain,
- d_i distance from the i^{th} element of the array at which estimates of power density are desired,
- $\hat{u}(\theta_i,\varphi_i)$ unitary vector of the i^{th} element,
- λ wavelength of the electromagnetic wave, [m]
- ${}_I G_M$ maximum gain of the antenna,
- $D_{Ve}(\theta)$ element radiation pattern in the vertical plane,
- $D_{He}(\varphi)$ element radiation pattern in the horizontal plane,
- ϕ_i phase difference between the element feeding coefficients.

An evaluation of the radiation pattern of the single antenna radiating elements is presented in [BiGi99]. Results were assessed with Numerical Electromagnetic Code (NEC) simulations, presenting good agreement for distances above three wavelengths. Nevertheless, the environment topology is not considered, in particular surrounding buildings, which may have an effect on the field levels.

4.3.6 Synthetic and gain based models

In [ABDK02], two simple models for BS panel antennas, denoted as *synthetic* and *gain-based* models, are proposed for human-exposure assessment.

In the synthetic model, the radiated near-field of one unit cell of the antenna array is calculated in the volume of interest; the near field of the full antenna array is then derived by superposing horizontally shifted field contributions of the unit cell. The model showed to be accurate for one wavelength away from the antenna, when compared with a full-wave analysis of the antenna array.

The second model, the gain-based one, is derived from the synthetic model. Instead of computing the radiated near-field of an element, the far-field radiation pattern is used. 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:

$$E(d,\theta,\varphi) \simeq \sum_{i=1}^{N} \frac{\sqrt{30 P_{in\ i} \cdot G_e(\theta_i,\varphi_i)}}{d_i} \mathrm{e}^{j(kd_i+\psi_i)}\, \hat{u}(\theta_i,\varphi_i), \quad d > 2\,\lambda \tag{4.14}$$

where:

- $E(d,\theta,\phi)$ rms electric field, [V/m]
- N number of radiating elements of the collinear array,
- $P_{in\ i}$ input power to the the i^{th} unit cell,
- $G_e(\theta_i,\varphi_i)$ radiating sector panel gain,
- d_i distance from the i^{th} element of the array at which estimates of power density are desired,
- ψ_i associated phase shift,
- $\hat{u}(\theta_i,\varphi_i)$ unitary vector of the i^{th} element,
- λ wavelength of the electromagnetic wave, [m]

This model approximates reasonably well the near field at a distance of about two wavelengths away from the antenna, requiring short computation time.

4.3.7 Hybrid prediction

In [BCFF99] and [BCDF02] a hybrid prediction algorithm is proposed for evaluation of field strength distributions near BS antennas. It combines different propagation models for diverse ranges of distances from the antenna: very near the antenna, in the near field region, and in the far field region.

For the near field region of a single antenna element ($d << \lambda$) the spherical waves triples model [Sche43] enables to evaluate the exact value of the electrical field radiated by a dipole as the sum of the field radiated from three different sources of spherical non-uniform waves, located in the middle and at the extremes of the dipole. It allows a rigorous prediction in both the near- and far-field regions of the antenna. As the environment is not taken into account, the analysis is limited to receiving points very close to the antenna.

For the area corresponding to the intersection between the far-field region of each element and the near-field region of the whole antenna ($d >> \lambda$ and $d < 2D^2/\lambda$), the sub-element radiation pattern antenna model [CGLM99] is combined with a ray-tracing propagation tool. At a given point, the total field is evaluated as the sum of all different contributions originated from each single sub-element, which is assumed as an independent non-uniform spherical source. The effect of reflections and diffractions due to obstacles near the antenna is accounted for through the combination of this antenna model with a ray-tracing algorithm.

For the area corresponding to the far-field region ($d > 2D^2/\lambda$) a ray tracing algorithm is used. This algorithm considers that propagation occurs by “rays”, experiencing reflection, transmission and diffraction effects due to the presence of obstacles. Nevertheless, it requires a detailed description of each obstacle by its electromagnetic properties. The total field is obtained as the vector sum of all contributions (rays) reaching the receiver.

The reliability of this hybrid prediction tool has been assessed with measurements. Based on this tool, an exclusion zone is derived as being a parallelepiped volume around the antenna. A preliminary evaluation of this precautionary volume is proposed, where distances for the different axis of this volume are specified for different installation types (mast, roof of a rural building, roof of an urban building with and without surrounding buildings), as presented in Figure 4.3. It should be noted that the limit for the rms value of the electrical field at 900 MHz is 20 V/m in Italy (place where this study was performed), while in Portugal it is of 41.25 V/m (value recommended by CENELEC and ICNIRP), resulting for Portugal in a smaller volume for the exclusion zone. It has been concluded that environment topology can slightly increase the field strength levels in real cases with respect to a free space case.

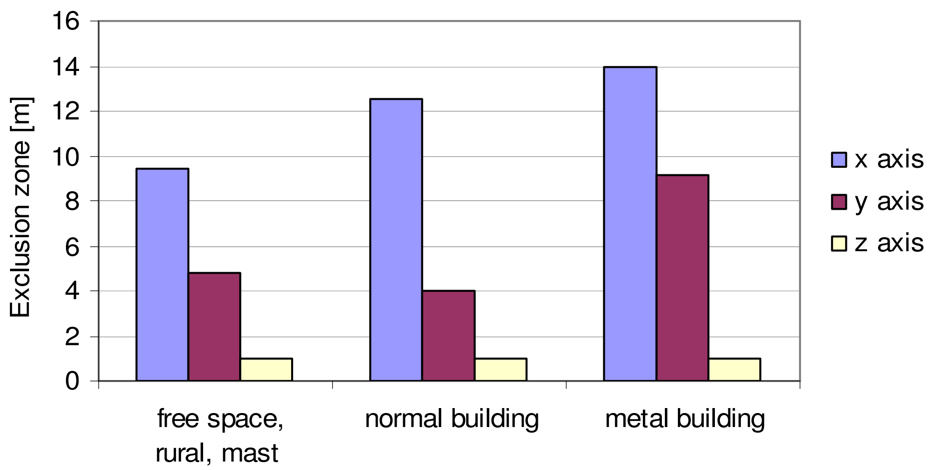


Figure 4.3 – Axis of the exclusion zone parallelepiped considering the threshold of 20 V/m (extracted from [BCFF99]).

4.3.8 Model for penetrable objects

In [BCCP03], a technique combining uniform asymptotic theory of diffraction and finite-difference time-domain, allowing an accurate evaluation of field interaction with penetrable objects (walls, windows, furniture, etc.) and of power absorption in a high-resolution model of the exposed subject, is presented. The results have shown that in a realistic exposure condition both whole-body and locally averaged SAR values are related to the average exposure field, and that the average field level decreases as compared with the equivalent free-space condition. It is further suggested that a free-space model would be sufficient for a conservative safety assessment.

4.3.9 Comparison of models validity range

Table 4.2 presents the respective ranges of validity of the surveyed models. It can be seen that the cylindrical exclusion model has a broader validity range, the definition of the corresponding exclusion zones being also very simple.

Table 4.2 – Validity range of the different surveyed propagation models.

	Propagation models validity range (expression of the power density)							
Validity range [m]	0	$\frac{\lambda}{2}$	λ	2λ	3λ	$\frac{D^2}{4\lambda}$	$\frac{\alpha_{3dB} G(\theta,\phi) D}{4\pi}$	$\frac{2D^2}{\lambda}$
Far-field model								
Far-field Approximation								
Far-field gain-based model								
Gain based model								
Synthetic based model								
Cylindrical exclusion zone								
Hybrid								

4.4 Perspectives from Other Entities

Several international or national entities have issued recommendations or guidelines for the definition of exclusion zones around BS antennas. An overview on some of these is presented next.

The French Ministry for Health and Social Security issued a report [MSPS01] presenting security perimeters around BS antennas for different BS types (considering typical antennas and radiated power):

- For a rural omni-directional macro-cell, a cylindrical exclusion zone of 3 m radius and 2 m above and below the antenna is defined for both 900 and 1800 MHz;
- For an urban macro-cell mounted on a roof-top or building façade, working at 900 and 1800 MHz, safety distances around the antenna respectively of 3 m and 1.5 m (front), 1 m and 0.5 m (side), 0.5 m and 0.3 m (back, below and above) are defined;
- For micro-cells, safety distances around the antenna of 0.5 m for front, side, back, below and above are defined;
- For pico-cells, safety distances around the antenna of 0.3 m for front, side, back, below and above are defined;
- For two pico-cells nearer than 5 m, safety distances around the antennas of 4.5 m (front), 1.5 m (side) and 0.5 m (back, below and above) are defined.

This is followed by all French operators. The exclusion zone is only marked out if it is accessible to public. Nevertheless, these distances depend on the antenna type being considered and its associated power. In the case of installation of several antennas on the same site, a cumulative effect might exist in the immediate proximity. In this case, specific exclusion zones are defined. In particular, the beam of greatest intensity should not be pointing to a sensitive area (schools grounds, hospitals or kindergartens where people spend several hours daily) nearer than 100 m.

The National Radiological Protection Board (NRPB) [NRBP04] is an independent body that has responsibility for advising UK Government departments and others on standards of protection for exposure to IR and NIR. It states that, for large macro-cell BSs radiating up to 100 W or more, exclusion zones in the range 10-15 m may be required in front of the antennas to ensure exposures remain within the ICNIRP guidelines for public exposure. In other directions, such as below and behind the antennas, the exclusion zones would extend for lower distances. Low power micro-cell BSs radiating around 1-2 W would require much smaller exclusion zones than macro-cells, and it may be possible to fully encompass all regions where exposure could exceed guidelines within the plastic cover of the antenna.

For the Independent Expert Group on Mobile Phones (IEGMP) in the UK, [RaWh04], most BSs are surrounded by perimeter fences, and exposures at the boundary are approximately 300-fold lower than the ICNIRP reference levels. Masts often also carry line-of-sight microwave communication dishes. These are highly directional low power devices, and the exclusion zones typically do not extend beyond the mouth of the dish. For urban micro-cells, low power BSs covering a small area, usually less than 50 m in diameter, exclusion zones are usually around 0.1 m from the antennas.

4.5 Estimation of Exclusion Zones

The first step to perform the calculations of the exclusion zones is to gather all the data from the antennas being used. For such, the Portuguese mobile phone operators were asked to supply the different parameters of the typical antennas that are being used in their networks. After that, the parameters supplied by the different operators were put together, this way obtaining typical values for the calculations.

The antennas parameters used in the calculations are presented in Table 4.3, where three installation scenarios were considered, trying to use the same results in similar types of antennas.

This document is a simple approach to the estimation of exclusion zones, therefore, only simple models, like the far field one, are used to perform calculations. The values are obtained for the worst case scenario, in the direction of the main lobe of the antenna. In order to obtain the distance values for the exclusion zones on the sides and on the back of the antennas, one needs to apply correction factors, which depend on the direction considered. A representation of the exclusion zone of an antenna is presented in Figure 4.4, as well as the different distances in the various directions.

Table 4.3 – Typical parameters of the antennas used to perform the calculations.

Rtower/RTower			
Type of System	GSM 900	GSM 1800	UMTS
Frequency Bandwidth [MHz]	870 – 960	1 710 – 1 880	1 920 – 2 170
BS EIRP (Maximum) [W]	1 000	600	630
Number of Sectors	3	3	3
Half Power Beam Width [º]	65	65	65
Gain [dBi]	17	17	18
Height/width/depth [mm]	1 936 / 262 / 116	1 936 / 262 / 116	1 302 / 155 / 69
Tilt [º]	0 - 8	0 - 8	0 – 8
URoof			
Type of System	GSM 900	GSM 1800	UMTS
Frequency Bandwidth [MHz]	880–960	1 710–1 880	1 920 – 2170
BS EIRP (Maximum) [W]	1 000	600	630
Number of Sectors	3	3	3
Half Power Beam Width [º]	65	65	65
Gain [dBi]	17	17	18
Height/width/depth [mm]	1 916 / 262 / 139	1 916 / 262 / 139	1 302 / 155 / 69

Tilt [º]	0 - 6	0 - 6	0 – 8

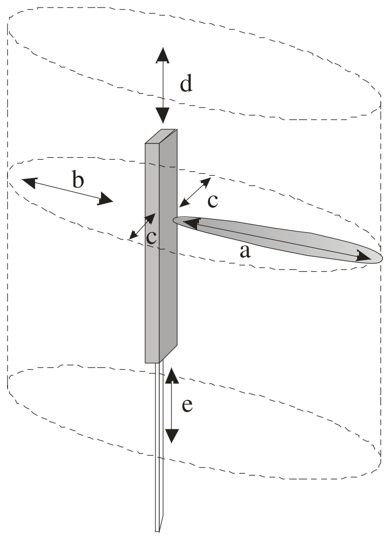
Table 4.3– Typical parameters of the antennas used to perform the calculations. (cont.)

Iceil			
Type of System	GSM 900	GSM 1800	UMTS
Frequency Bandwidth [MHz]	860–960	1 710–1 880	1 920 – 2 170
BS EIRP (Maximum) [W]	3.17	3.17	3.17
Number of Sectors	1	1	1
Half Power Beam Width [º]	360	360	360
Gain [dBi]	2	2	2
Height/radius [mm]	205/67	205/67	205/67
Tilt [º]	0	0	0

In the beginning of each particular case, one must estimate the far field region of the antennas, in order to check if the far field model can be used. The obtained distances for the far field region are around 20 m for GSM 900 and UMTS, and around 40 m for GSM 1800. At these distances, the power density in the worst case, calculated using the far field model [CENE02], is around 20 times below the threshold values established by the ICNIRP [ICNI98]. A consequence of these results is that there is a need to use other models valid at a closer distance from the antennas.

Another model presented in the last section is the far field approximation, [MNMV02]. The minimum distance of this model's validity range, $D^2/4\lambda$, is 8 times smaller than the far field model, where D is the maximum dimension of the antenna and λ is the wavelength of the electromagnetic wave. This model allows one to obtain results at a much closer distance from the antennas, and the results obtained are presented in Table 4.4.

As it can be seen for the Iceil scenario, the obtained values in the minimum valid distance are already above the threshold, so, the exclusion zone will be larger. In the other two scenarios, the obtained values are still below the threshold, but for simplicity and precautionary reasons, this model is still used in this report, considering the exclusion zone as being the minimum valid distance of the model.



a=D_{front}

b=D_{back}

c=D_{side}

d=D_{top}

e=D_{bottom}

Figure 4.4 – Representation of an antenna's exclusion zone.

Table 4.4 – Values obtained using the far field approximation model.

Rtower/Utower					
	EIRP [W]	$D^2/4\lambda$ [m]	S [W/m^2]	S/S_{max}	
GSM 900	1 000	3.00	1.515	0.316	-5.00 dB
GSM 1800	600	5.87	0.464	0.049	-13.10 dB
UMTS	630	3.07	1.103	0.110	-9.59 dB
Uroof					
	EIRP [W]	$D^2/4\lambda$ [m]	S [W/m^2]	S/S_{max}	
GSM 900	1 000	2.94	1.563	0.326	-4.87 dB
GSM 1800	600	5.75	0.479	0.051	-12.92 dB
UMTS	630	3.07	1.103	0.110	-9.59 dB
Iceil					
	EIRP [W]	$D^2/4\lambda$ [m]	S [W/m^2]	S/S_{max}	
GSM 900	3.17	0.03	23.094	4.811	6.82 dB

GSM 1800	3.17	0.07	11.793	1.255	0.99 dB
UMTS	3.17	0.08	10.217	1.022	0.09 dB

For the Iceil scenario, the distance of the exclusion zone can be calculated by estimating the distance from the antennas where the power density value equals the threshold value. The calculation results are presented in Table 4.5 and in Figure 4.5. For the Iceil scenario, there is no need to calculate other values than D_{front}, because the antennas are omni directional, thus making the exclusion zone circular. So, the exclusion zone values are the ones presented in Table 4.5.

Table 4.5 – Exclusion zone for the Iceil scenario.

	EIRP [W]	D_{front} [m]
GSM 900	3.17	0.18
GSM 1800	3.17	0.09
UMTS	3.17	0.08

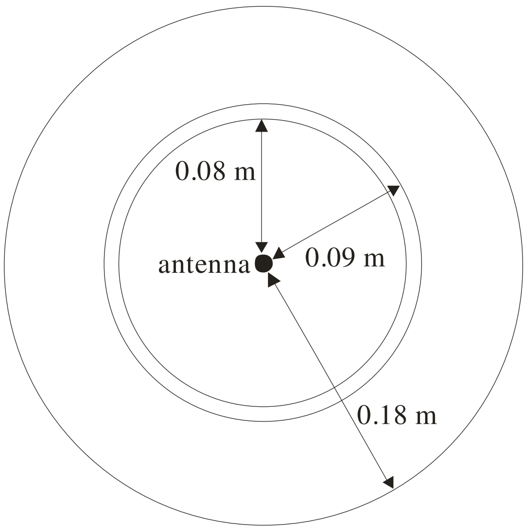


Figure 4.5 – Drawing of the exclusion zone for the Iceil scenario.

It is now possible to calculate and present the exclusion zones of the different scenarios considered, presenting also, for each case, the distances for the various directions, as it is shown in Figure 4.4. The distance values for the other considered directions are calculated based on the D_{front} value, but applying corrections factors, Table 4.6. For the sides and back of the antenna, the correction factors are based on typical antennas characteristics as stated in an antennas catalogue [KATH04]. For the sides, -10 dB is used for the correction factor, this being the typical value for a 130º beam width. For the back, -15 dB is used as the correction factor, corresponding to the relative value of the second biggest radiation lobe. These two values correspond to 0.1 and 0.032 in linear values, respectively. As stated in Section 4.3.4, for the top and back (D_{top} and D_{bottom}) the values used are $0.3D_{front}$. When a downtilt θ_{dt} is used, the correction of these values are suggested in expressions (4.9) and (4.10).

Table 4.6 – Exclusion zones for the Rtower/Utower and Uroof scenario.

RTower/Utower					
	D_{front} [m]	$D_{back}=0.032D_{front}$ [m]	$D_{side}=0.1D_{front}$ [m]	$D_{top}=0.3D_{front}$ [m]	$D_{bottom}=0.3D_{front}$ [m]
GSM 900	3.00	0.09	0.30	0.90	0.90
GSM 1800	5.87	0.19	0.59	1.76	1.76
UMTS	3.07	0.10	0.31	0.92	0.92
Uroof					
	D_{front} [m]	$D_{back}=0.032D_{front}$ [m]	$D_{side}=0.1D_{front}$ [m]	$D_{top}=0.3D_{front}$ [m]	$D_{bottom}=0.3D_{front}$ [m]
GSM 900	2.94	0.09	0.29	0.88	0.88
GSM 1800	5.75	0.18	0.58	1.73	1.73
UMTS	3.07	0.10	0.31	0.92	0.92

Scenarios with more than one carrier are also considered, the cumulative effect of 4 carriers for each scenario being considered in this report. Even considering the cumulative effect of multiple carriers, the distances for the exclusion zones remain the same in almost all the scenarios analysed, because the results obtained with the model are still smaller than its minimum valid distance. As it has already been stated, when this happens the distance considered for the exclusion zone is the model minimum valid distance. The distances increased a bit just for the Iceil scenario and for the GSM 900 system in all the other scenarios, the new values for these situations being presented in Table 4.7. For the Iceil scenario, as it has already been seen before, there is no need to calculate other values than D_{front}, because the antennas are omni directional, thus, making the exclusion zone circular.

In the situations with co-location of antennas, the sum effect of the different sources of radiation must be taken into account. Three different scenarios were considered, with co-location of GSM 900/GSM 1800, GSM 900/UMTS and GSM 900/GSM 1800/UMTS. In each scenario, the distance being considered must be equal or higher than the distance where the used model can still be applicable in all the co-located systems. The exclusion zone is given by the same model used before, or if the obtained distance is not valid, the exclusion zone is given by the model minimum valid distance.

Table 4.7 – Exclusion zones considering the existence of 4 carriers in each system.

RTower/Utower					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
GSM 900	4.18	0.13	0.42	1.25	1.25
GSM 1800	5.87	0.19	0.59	1.76	1.76
UMTS	3.07	0.10	0.31	0.92	0.92
Uroof					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
GSM 900	4.17	0.13	0.42	1.25	1.25
GSM 1800	5.75	0.18	0.58	1.73	1.73
UMTS	3.07	0.10	0.31	0.92	0.92
Iceil					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
GSM 900	0.72	-	-	-	-
GSM 1800	0.36	-	-	-	-
UMTS	0.32	-	-	-	-

The results for the exclusion zones for the different directions of the antennas are calculated exactly as before, using the same correction factors. Scenarios with multiple carriers are also considered for the situations with co-location of antennas, the effect of using 4 carriers for each system being studied once again. The obtained values for all the situations considered are presented in Table 4.8, Table 4.9 and Table 4.10.

Table 4.8 – Exclusion zones for the scenarios with co-location of GSM 900/GSM 1800 with 1 and 4 carriers in each system.

RTower/Utower					
	D_{front} [m]	$D_{back}=0.032D_{front}$ [m]	$D_{side}=0.1D_{front}$ [m]	$D_{top}=0.3D_{front}$ [m]	$D_{bottom}=0.3D_{front}$ [m]
1 carrier	5.87	0.19	0.59	1.76	1.76
4 carriers	5.87	0.19	0.59	1.76	1.76
Uroof					
	D_{front} [m]	$D_{back}=0.032D_{front}$ [m]	$D_{side}=0.1D_{front}$ [m]	$D_{top}=0.3D_{front}$ [m]	$D_{bottom}=0.3D_{front}$ [m]
1 carrier	5.75	0.18	0.58	1.73	1.73
4 carriers	5.75	0.18	0.58	1.73	1.73
Iceil					
	D_{front} [m]	$D_{back}=0.032D_{front}$ [m]	$D_{side}=0.1D_{front}$ [m]	$D_{top}=0.3D_{front}$ [m]	$D_{bottom}=0.3D_{front}$ [m]
1 carrier	0.27	-	-	-	-
4 carriers	1.09	-	-	-	-

Table 4.9 – Exclusion zones for the scenarios with co-location of GSM 900/UMTS with 1 and 4 carriers in each system.

RTower/Utower					
	D_{front}	$D_{back}=0.032D_{front}$	$D_{side}=0.1D_{front}$	$D_{top}=0.3D_{front}$	$D_{bottom}=0.3D_{front}$

	[m]	[m]	[m]	[m]	[m]
1 carrier	3.07	0.10	0.31	0.92	0.92
4 carriers	5.59	0.18	0.56	1.68	1.68

Table 4.9 – Exclusion zones for the scenarios with co-location of GSM 900/UMTS with 1 and 4 carriers in each system. (cont.)

Uroof					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
1 carrier	3.07	0.10	0.31	0.92	0.92
4 carriers	5.58	0.18	0.56	1.67	1.67
Iceil					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
1 carrier	0.26	-	-	-	-
4 carriers	1.05	-	-	-	-

Table 4.10 – Exclusion zones for the scenarios with co-location of GSM 900/GSM 1800/UMTS with 1 and 4 carriers in each system.

RTower/Utower					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
1 carrier	5.87	0.19	0.59	1.76	1.76
4 carriers	6.86	0.22	0.69	2.06	2.06
Uroof					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
1 carrier	5.75	0.18	0.58	1.73	1.73
4 carriers	6.87	0.22	0.69	2.06	2.06

Table 4.10 – Exclusion zones for the scenarios with co-location of GSM 900/GSM 1800/UMTS with 1 and 4 carriers in each system. (cont.)

Iceil					
	D_{front} [m]	D_{back}=0.032D_{front} [m]	D_{side}=0.1D_{front} [m]	D_{top}=0.3D_{front} [m]	D_{bottom}=0.3D_{front} [m]
1 carrier	0.35	-	-	-	-
4 carriers	1.41	-	-	-	-

5. CONCLUSIONS

In the present document, an overview on the definition of exclusion zones around GSM and UMTS BS antennas is presented, defining areas within which EMFs exposure guidelines are exceeded, in order to protect public in general from potential harmful levels of radiation.

A classification of different types of BS antennas installations is presented in order to typify the possible configurations of the exclusion zones. Types of installation consider the type of structure where the antenna is installed, the environment and the type of cell. Essential parameters are also identified for the estimation of the exclusion zone: site topology, system, number of carriers and Tx and Rx antennas, transmitter maximum output levels, antenna characteristics.

A discussion on biological effects of EMFs is also presented. Radio frequency is a NIR, where possible biological effects are the thermal and the non-thermal ones. Thermal effects are well known and quantifiable by means of SAR. ICNIRP issued guidelines presenting safety thresholds for human exposure to EMFs, below which damages due to the thermal effect do not occur. These values have been adopted as recommended values by many countries, including Portugal. Non-thermal effects are being deeply studied by several scientific communities. No study, evidencing non-thermal effects of EMF, has been able to be replicated up to now. The occurrence of long-term biological effects is also an open issue.

The theme of exclusion zones around typical BS installations is introduced as well. Exclusion zones may be obtained either by measurements or by prediction. Measurements are time consuming and BS dependent, leading one to proceed with the estimation of these zones through adequate models, to obtain a prediction of the EMFs radiated by an antenna or SAR. A survey on models found in the literature is presented. Based on these models, a methodology for estimating exclusion zones around typical BS antennas installations is suggested.

In this work, a simple and precautionary approach is taken, which leads, in most of the cases, to pessimistic results for the distance of the exclusion zones. Three different scenarios are considered (Rtower/Utower, Uroof and Iceil), in order to use the same results in similar types of antennas. For the first two scenarios, the results obtained are around 3 m for GSM 900 and UMTS typical antennas; for GSM 1800, the results obtained are around 5.8 m. For the Iceil scenario, the distances obtained are around 0.2 m for GSM 900 and 0.1 m for GSM 1800 and UMTS. The scenarios with co-location of antennas are also considered, but because of the model used, the distance obtained in the two first site types is the maximum distance where the used model can still be applicable in all the co-located systems. For the Iceil scenario with co-location, the distances obtained increased a bit up to 0.35 m for the case of co-location of all the three systems considered. The sum effect of using more than one carrier for the different systems is also considered, leading in some cases to an increase of the exclusion zone. For the scenario of co-location of all the 3 considered systems with 4 carriers per system the exclusion zone reaches almost 7 m.

However, one should note that these values are obtained for typical situations, and a detailed analysis needs to be performed for a specific location and antenna configuration.

ANNEX – BS SURVEY

Date: **Time:**

Address:

1. Site topology

Environment:

Rural / suburban □
Urban □
In-building □

Type of cell:

Macro □
Micro □
Pico □

Installation type:

Tower □
Mast □
Water sump □
"Tree" □
Other ____________

Denomination: ____________________

Roof-top □
Building façade □
Light pole □
Ceiling □
Walls □

2. Identification of circulation areas or other sensitive places

Kindergarten / school □ at __________ m
Hospital / health centre □ at __________ m
Elderly centre □ at __________ m
Public garden □ at __________ m
Sports-hall □ at __________ m
Other ___________________ at __________ m
Other ___________________ at __________ m

3. Type of system

GSM900 ☐

GSM1800 ☐

UMTS ☐

Other ______________

4. Sketch of the surrounding area

5. BS characteristics

Type of system			
Frequency bandwidth [MHz]			
Maximum output power level [dBm]			
Number of carriers per antenna			
Carrier(s) central frequency(ies) [MHz]			
Antenna type / no. of sectors			
Antenna reference			
Dimensions (L x W x H) [cm^3]			
Height [m]			
Azimuth [º]			
Tilt [º]			

Note: In case of co-location of Tx antennas of different systems / operators, the number of columns of this table needs to be replicated.

6. Other relevant information

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