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SCHOOL OF HEALTH SCIENCES

FACULTY OF MEDICINE

MEDICAL PHYSICS LAB

Head THEODOROU KYRIAKI

Ph.D. Thesis

«EXPOSURE AND ABSORPTION ESTIMATION OF LOW AND RADIO FREQUENCY ELECTROMAGNETIC FIELDS IN HUMAN TISSUES. EXPOSURE FROM NEW WIRELESS TECHNOLOGIES»

by

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It was submitted for the fulfillment of part of

the requirements for the Ph.D. acquisition

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Στους Αξιότιμους Καθηγητές μου

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- *Πώς πρέπει ν' αγαπούμε το Θεό;*
- *Αγαπώντας τους ανθρώπους.*
- *Πώς πρέπει ν' αγαπούμε τους ανθρώπους?*
- *Μοχτώντας να τους φέρουμε στο σωστό δρόμο.*
- *Ποιος είναι ο σωστός δρόμος;*
- ***Ο ανήφορος.***

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Brief CURRICULUM VITAE

Charilaos Tyrakis has been a Ph.D. candidate at the University of Thessaly School of Medicine since December 2017. He holds an MSc in "Medical Physics" from the University of Surrey (UK) and an MBA in "Techno-Economic Systems" from the National Technical University of Athens and Piraeus University. His BSc was in Physics sciences from the National and Kapodistrian University of Athens.

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Certified Engineer by the Hellenic Accreditation Body for Electromagnetic Fields Exposure measurements from 27 to 6000 MHz & Noise measurements according to ISO/IEC 17025 standard. He speaks English (fluent) and French (fluent). He is married with two children, Margarita and Dimitris.

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«HUMAN EXPOSURE AND ABSORPTION ASSESSMENT FROM LOW AND RADIO-FREQUENCY ELECTROMAGNETIC FIELDS. EXPOSURE FROM NEW WIRELESS TECHNOLOGIES»

CHARILAOS D. TYRAKIS

University of Thessaly, Faculty of Medicine, 2023

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Abstract

Electromagnetic fields (EMFs) are among the top issues of public concern. Non-ionizing EMF radiation becomes an essential area of investigation as wireless technologies evolve continuously. The penetration of mobile communications is enormous, with a vast number of applications and services available. The scope of this Ph.D. work was to measure (and then evaluate) both Low-Frequency (LF) and Radiofrequency (RF) radiation levels (up to 3000 MHz) in areas of sensitive land use in Greece. This project was a major part of the National EMF research program (EDBM34) with the participation of the Medical Physics Lab of the University of Thessaly (Faculty of Medicine). A thousand (1000) spots were selected for the RF part, while 247 were selected for the LF part. We evaluated human safety by comparing the exposure values with the latest, updated safety limits of ICNIRP issued in 2020 and the adopted Greek limits, which are stricter than the ICNIRP's guidelines. Spectrum analyzers were used in both projects providing detailed information on the emissions present in the environment. During the current Ph.D. thesis, 5G networks started to be deployed in Greece at 700 MHz, 2100 MHz, and 3500 MHz (known as C-band). Our study in 5G was based on a few indicative measurements. Moreover, we reviewed the most important international 5G surveys, investigating the possible increase in human exposure caused by 5G technologies, including the evolution of the Internet of Things (IoT). Based on all the experimental and theoretical data, this Ph.D. thesis concluded on human safety in LF and RF spectrum area, considering the legacy and the new wireless technologies that are expected to exhibit wide use in Greece in the forthcoming years. The current state of knowledge, derived from this Ph.D. work, supports that the new wireless technologies are not expected to considerably change the EMF background in residential and outdoor environments. All measurements results were well below the strictest Greek safety limits for all the spectrum bands investigated. A review of the scientific literature was also a part of the current thesis, including the updated safety guidelines by ICNIRP (2020). In the following years, re-evaluating the RF exposure levels, at the locations already measured,

will provide the scientific community with more detailed information on the RF environment due to 5G emissions (more 5G antennas will be installed, more subscribers will use these services). The focus should also be given to the new spectrum that will be used in 5G, above 24 GHz, known as millimeter wave (mmWave) radiation.

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PART ONE: GENERAL PART

Chapter 1: EMF Interaction with Human Tissue and Dosimetry

1.1 Basic Principles

Electric (EF) and magnetic (MF) fields interact with materials in two ways [1]. First, The EF and MF fields exert forces on the charged particles in the materials, thus altering the charge patterns that initially existed. Second, the modified charge patterns in the materials produce additional EF and MF (in addition to the originally applied fields). Materials are usually classified as being magnetic or nonmagnetic. Magnetic materials have magnetic dipoles strongly affected by applied MFs; nonmagnetic materials do not. In non-magnetic materials (human tissue), mainly the applied E-field influences the charges in the material. This occurs in three primary ways:

1. Polarization of bound charges (charges in a solid that cannot move around and conduct current)

2. Orientation of permanent dipoles (for example H^+ Cl^-)

3. Drift of conduction charges (both electronic and ionic)

Materials primarily affected by the first two cases are called dielectrics; materials primarily affected by the third are called conductors. Dielectrics are materials that don't allow current to flow. They are often called insulators because they are the opposite of conductors. But usually, when people call insulators “dielectrics,” they want to draw attention to a special property all insulators share: polarization ability. Concerning the 3 ways of interacting:

A. The polarization of bound charges is illustrated in Fig. 1.1 (left). Bound charges are so tightly bound by restoring forces in a material that they can move only very slightly. Without an applied E-field, positive and negative bound charges in an atom or molecule are essentially superimposed upon each other and effectively cancel out; but when an E-field is applied, the forces on the positive and negative charges are in opposite directions, and the charges separate, resulting in an induced electric dipole.

B. The orientation of a permanent dipole is illustrated in Fig. 1.1 (right). With no E-field applied, the permanent dipoles are randomly oriented because of thermal excitation. With an E-field applied, the resulting forces on the permanent dipoles tend to align the dipole with the applied E-field.

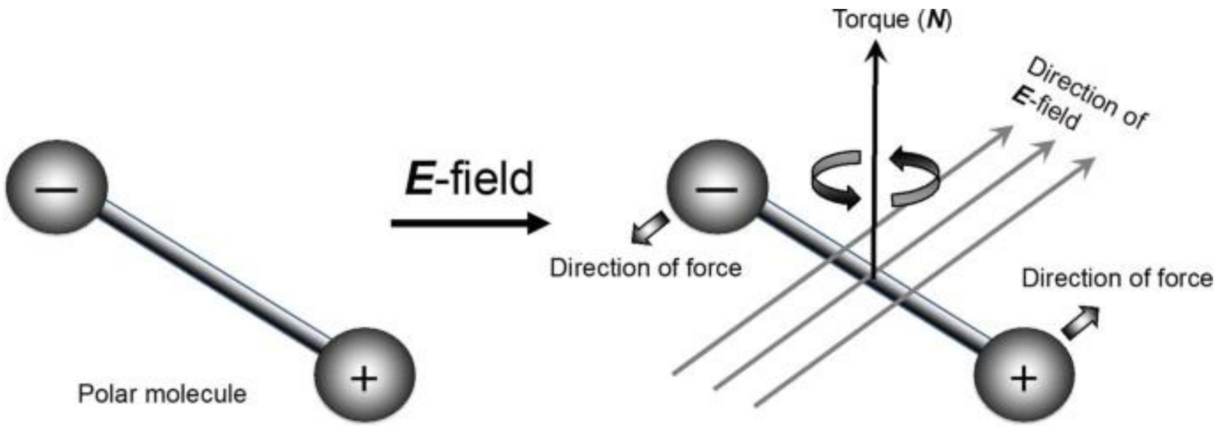

Figure 1.1. Formation of a dipole when an external Electric field (E) is applied to a dielectric material and the orientation of the permanent dipole. Image from Horikoshi, S., Serpone, N. (2022). Microwave Thermal and Nonthermal Processes. https://doi.org/10.1007/978-981-16-3891-6_1

C. The drift of conduction charges in an applied E-field occurs because these charges are free enough to rove significant distances in response to the forces of the applied fields. Both electrons and ions can be conduction charges. The drift of conduction charges forms a current, and the current flow produces a new field that did not exist before the initial E-field was applied. Based on the above notes, two quantities describe the material's role in energy absorption: permittivity and conductivity. Free charge movement leads to conductivity, whereas stationary dipoles are related to permittivity.

Permittivity (ε_s): Permittivity is the property of the material that indicates its ability to form dipoles and exhibit polarization when an EF is applied [1]. Permittivity generally decreases with frequency (Fig. 1.2). Complex permittivity is a property that describes both polarization and absorption of energy. The real part is related to polarization and the imaginary part to energy absorption (the absorption leads to the "dielectric loss": loss of energy that goes into heating a material in a varying EF). The following equation (1) describes the quantity complex permittivity, which accounts for both dipole charges and conduction-charge drift.

$$\varepsilon_s = \varepsilon_0 \, (\varepsilon'(\omega) - i\varepsilon''(\omega)) \text{ Farad/m} \qquad (1)$$

where: $\omega = 2\pi f$ (rad/sec) and $i = \sqrt{-1}$

Note: ε' and ε'' are the real and imaginary components, respectively, ω is the radial frequency (rad/s) that can be easily converted to frequency (Hz), ε_0 is the permittivity of free space, and ε' is also called the dielectric constant. The ε' of a material is primarily a measure of the relative amount of polarization that occurs for a given applied E-field, and the ε'' is a measure of both the friction related to the changing polarization (the friction is associated with the alignment of electric dipoles and with vibrational and rotational motion in molecules) and the drift of conduction charges. Moreover, the imaginary part is related to the conductivity:

$$\varepsilon'' = \sigma / \omega^* \varepsilon_0 \qquad (2)$$

where σ is the conductivity (or effective conductivity).

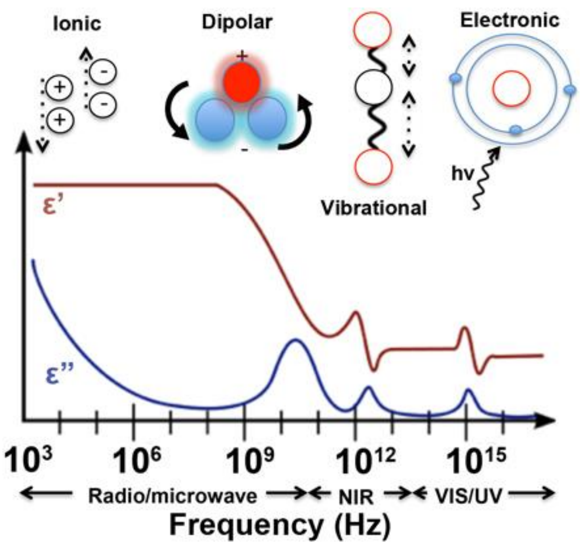

Figure 1.2. Frequency response of dielectric mechanisms. Water molecules are permanent dipoles, which rotate to follow an alternating electric field. Image from Basics of measuring the dielectric properties of materials, Hewlett Packard literature number 5091-3300E, 1992.

Conductivity [2]: Conductivity indicates the drift of conduction charges inside the material (a measure of the ability to conduct or transmit electricity or heat). The movement of free charge produces conductivity, whereas stationary dipoles produce permittivity. In steady state the distinction between the two is clear, but at higher frequencies the concepts merge. In such a case, we can combine the electrical properties into a complex conductivity, σ′. Complex conductivity is given by:

$$\sigma' = \sigma + i\omega\varepsilon \qquad (3)$$

Where ω (rad/s) is the angular frequency (ω= 2πf, where f is the frequency in Hz) and i is √-1. The real part of σ′ accounts for the movement of charge that is in phase with the electric field; the imaginary part accounts for out-of-phase motion. Both the real and the imaginary parts of the complex conductivity may depend on the frequency. For many bioelectric phenomena, the first term in the equation is much larger than the second so that the tissue can be represented as purely conductive. Rule of thumb: Penetration depth decreases as conductivity increases and frequency increases.

The following paragraphs will present a more detailed approach to EMF interaction with biological tissue and possible biological and health effects. Of course, different EMF bands lead to different interaction mechanisms and effects. Three different areas of the spectrum will be analyzed. Static fields (SF), Low frequency and Extremely Low-Frequency fields (LF and ELF), and Radiofrequency fields (RF).

1.2 The Electromagnetic Spectrum and Health Effects

The electromagnetic spectrum (Fig. 1.3) is divided into two areas: the non-ionizing radiation and the ionizing. Non-ionizing EMFs have no sufficient energy to break molecular bonds and remove electrons from atoms or molecules. Above the frequency of 3×10^{15} Hz [3] the situation is changed, and the photon energy (above 10 eV) is sufficient to produce ions, which may act directly on the cellular component molecules or indirectly on water molecules, causing water-derived radicals. Radicals react with nearby molecules in a very short time, resulting in the breakage of chemical bonds or oxidation (addition of oxygen atoms) of the affected molecules. The non-ionizing part of the electromagnetic spectrum up to 300 GHz comprises static fields SF (0 Hz) and low-frequency fields LF (up to approximately 300 Hz), the intermediate-frequency IF range between about 300 Hz and 100 kHz, and the radiofrequency range RF from 100 kHz to 300 GHz. The distinguishing line between the low-frequency and radiofrequency bands is 10 MHz. Terahertz (THz = 10^{12} Hz) waves between 300 GHz and 10 THz (wavelengths from 1 mm to 30 μm) are used for quality control of industrial products, at some airports in body scanners for security control, or in skin cancer scanning systems. Ultraviolet (UV) radiation (100–400 nm), visible light (400–780 nm), and infrared radiation (wavelengths 780 nm–1 mm) are found at the edge of the non-ionizing spectrum.

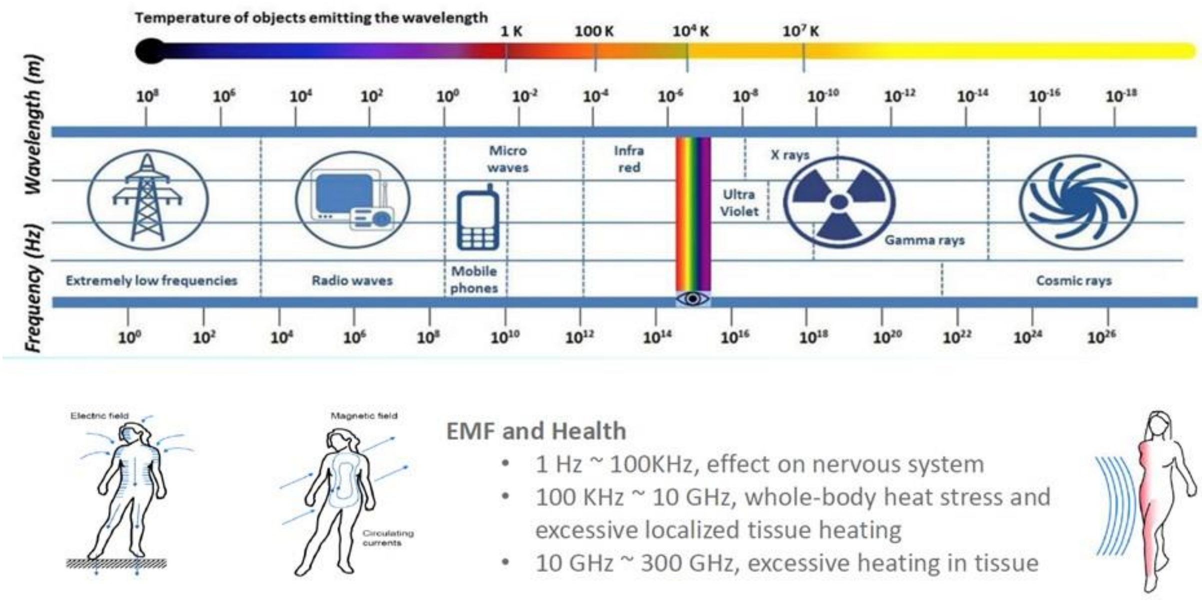

Figure 1.3. The Electromagnetic Spectrum. Ionizing radiation starts from 10^{16} Hz: Saliev, T., Begimbetova, D., Masoud, A. R., & Matkarimov, B. (2019). Biological effects of non-ionizing electromagnetic fields: Two sides of a coin. Progress in biophysics and molecular biology, 141, 25–36.

The following Table 1.1 summarizes the possible effects and symptoms [4] from the non-ionizing part (up to 300 GHz – RF bands).

Table 1.1. Possible effects and symptoms caused by EMFs

Field	**Frequency**	**Possible Effects / Symptoms**
Static magnetic fields	0-1 Hz	Interference with medical devices Movement leads to nausea and vertigo, metallic taste (>2-4T) Effects on blood flow (1% reduction in aortic blood flow at 5T), Heart rate effect (> 8T), brain function (> 7 T) Nerve stimulation (24 T) Muscle contraction (fast movements)
Low frequency magnetic fields	1 Hz – 10 MHz	Interference with medical devices Visual sensations Nerve stimulation / tingling sensation or pain Muscle contraction, heart arrhythmia
Low frequency electric fields	1 Hz – 10 MHz	Electric shocks, stress
High frequency fields	Above 100 kHz	Interference with medical devices Sensation of warmth Heat stress Electric shocks Other

1.3 Static Fields (0 Hz)

Static fields (0 Hz) are created by charges that are fixed in the air. A static magnetic field (MF) is created by a magnet or charges that move in a steady flow (as in appliances using direct current).

1.3.1 Static Fields Interactions with Biological Tissue and Health Effects

Static Electric Field (EF) Interaction: According to WHO Environmental Health Criteria on Static fields (2006) and ICNIRP guidelines on limits of exposure to static magnetic fields (2009), static EFs cannot penetrate the body because they discharge at the surface due to the high body conductivity. However, because of the high conductivity of body tissues relative to air, exposure to a static electric field does not produce a significant internal field but leads to the buildup of surface charge on the body. The induced surface charge may be perceived if discharged to a grounded object. Painful microshocks can be expected when a person who is well insulated from the ground touches a grounded object, or when a grounded person touches a conductive object that is well insulated from ground. Hairs are moved, they repel each other, and then they straighten up. However, the threshold static electric field values will vary depending on the degree of insulation and other factors. The human sensing threshold ranges from 10 to 45 kV/m [5]. As a direct health effect of static EFs, stress is reported that can be derived due to prolonged exposure to microshocks. However, so far, no harmful effects have been reported in human and animal laboratory studies [5].

Static Magnetic Field (MFs) Interaction: Two types of interactions may occur: a) Electrodynamic interactions that originate through the interaction of MF with electrolyte flows, leading to the induction of electrical potentials and currents, and b) Magnetomechanical phenomena including orientation effects on macromolecular assemblies in fields, and the movement of paramagnetic and ferromagnetic molecular species in strong field gradients.

A) Electrodynamic effects:

According to WHO Environmental Health Criteria on Static fields (2006) and ICNIRP guidelines on limits of exposure to static magnetic fields (2009), static MFs penetrate most materials - including the body tissue – and may have an effect at any point within the body. Magnetic fields interact (forces are created – F_{Lorenz}) with moving charge carriers in the human body (e.g., ions in cells and body fluids, charges on cell surfaces, or electrically charged cells in the blood) and can produce electric potential and currents. This can cause perceptible but harmless effects at low strength magnetic fields. Blood flow creates electrical potentials that have been recorded in the ECGs of animals and volunteers placed in strong static magnetic fields. When a human is moving (fast or slow), electric fields are created in tissues, affecting nervous tissues. The magnitude of the induced electric fields depends on the temporal and spatial gradients. It is common to report dizziness (vertigo) when someone moves quickly in the magnetic field. That is why there are occupational guidelines not to walk rapidly in MRI (magnetic resonance Imaging) machines room. Tongue and taste may also be affected (metallic taste), while nausea is also a symptom. Altered brain and heart function are also included in symptoms. All these effects are transient and will be removed when the movement stops or slows down. To minimize the effects, the movement should be slow, and the external magnetic field should be of low strength (up to 2 T). Cardiovascular responses, such as changes in blood pressure and heart rate, have been occasionally observed in human volunteer and animal studies. However, these were within the range of normal physiology for exposure to static magnetic fields up to 8 T. Although not experimentally verified, three possible effects of induced electric (flow) potentials are reported: minor changes in the rate of heartbeat (which may be considered to have no health consequences), the induction of ectopic heart beats (which may be more physiologically significant), and an increase in the likelihood of re-entrant arrhythmia (possibly leading to ventricular fibrillation). The first two effects are thought to have thresholds above 8 T, while threshold values for the third are difficult to assess at present because of modelling complexity. Almost 5 - 10 per 10,000 people are particularly susceptible to re-entrant arrhythmia, and the risk to such people may be increased by exposure to static magnetic fields and gradient fields.

B) Magnetomechanical effects (significant mostly at flux densities greater than 1 T):

There are two basic mechanisms through which static magnetic fields exert mechanical forces and torques on objects. In the first type of magnetomechanical interaction, rotational motion of a substance occurs in a uniform field until it achieves a minimum energy state. The second mechanism involves the translational force exerted on a paramagnetic or ferromagnetic substance placed in a magnetic field gradient, although in theory the only requirement is that the object has a different magnetic susceptibility to its surroundings. This effect exhibits generally weak interactions because the magnetic susceptibility of most biological material is very small and therefore significant mostly at flux densities greater than 1 T.

C) Atomic and Subatomic level effect:

Two interactions take place. The nuclear magnetic resonance (NMR) and the effects on electronic spin states, and their relevance to certain classes of electron transfer reactions in living tissues. NMR is the basis or MRI (Magnetic Resonance Imaging) in diagnosis.

Earth's Electric and Magnetic field:

Natural MF is the earth's magnetic field, also known as the geomagnetic field (GMF), a quasi-static magnetic field that encloses our planet from the South Pole to the North Pole. It is caused mainly by electric currents in the liquid part of the Earth's core. At the Poles, the magnetic field is twice as strong as the equator. The geomagnetic field depends on the geological depth and latitude; on the Earth's surface, it ranges from 30-70 μT. Thus, the geomagnetic field is the strongest magnetic field we are continuously exposed to. Natural electric fields are also present on the Earth. Electric fields occur mainly between the ground and upper layers of the atmosphere (the ionosphere, from 70 km altitude). They are primarily caused by the radiation of the sun and by solar winds. The magnitude of the static electric field depends on the sun's activity, the air's conductivity, the season, and the weather. For example, during the winter, the field strength is 270 V/m, which is twice as high as in the summer (130 V/m). In contrast, during thunderstorms over a flat terrain, field strengths can reach 20,000 V/m with peaks of up to 300,000 V/m (during lightning). The huge electric field strengths are caused by heated, humid air masses in the thunderclouds. Sudden discharges by lightning result in electromagnetic impulses (sferics), measurable even in long distances [6].

Chronic or delayed effects from Static fields:

Electric fields: There are no studies of exposure to static EFs from which to make any conclusion on chronic or delayed effects. IARC (2002) noted that there was insufficient evidence to determine the carcinogenicity of static EFs.

Magnetic fields: Regarding static MFs, the available evidence from epidemiological and laboratory studies is not sufficient to draw any conclusions about chronic and delayed effects. IARC (2002) concluded that there was inadequate evidence in humans for the carcinogenicity of static magnetic fields, and no relevant data available from experimental animals. They are therefore not at present classifiable as to their carcinogenicity to humans.

1.3.2 Legislation and Safety Limits

Legislation in Greece is based on the following guidelines:

- EC Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). Official Journal of the European Community, L199/62, 1999.
- International Commission on Non-Ionizing Radiation Protection (ICNIRP). 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74:494–522.

- International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2009. ICNIRP guidelines on limits of exposure to static magnetic fields. Health Phys 96(4):504-514

Reference levels from 1998 and the updated ones since 2009 are presented. Greek legislation follows the 1998 version (Table 1.2).

Table 1.2. Reference (Safety) Limits issued by ICNIRP 1998 and 2009

<table>
<tr><th>f (Hz)</th><th>H (μT)</th><th>Comments</th></tr>
<tr><td>0 Hz static</td><td>4 x 10^4 μT
ICNIRP 1998</td><td rowspan="2">These fields are static. No limit is set for the electric field strength, but it is stated that for most people, the disturbing sensation of electric surface charges is not perceived in a region of less than 25 000 V/m. Spark discharges causing stress or annoyance should be avoided.</td></tr>
<tr><td>0 Hz static
Exposure to any part of the body</td><td>40 x 10^4 μT
ICNIRP 2009</td></tr>
</table>

1.4 Low Frequencies (LFs): 0.1 to 100 kHz

LFs are divided into Extremely Low Frequency (ELF) and Intermediate Frequencies (IF). ELFs range from 0.1 Hz to 300 Hz (standardized by World Health Organization – WHO). Sources of ELFs are power distribution lines, household wiring, and appliances. No natural sources exist for these bands. Electric and magnetic fields are studied separately at those low frequencies as they are not coupled. In Europe, power is distributed at 50 Hz, while in North and Middle America, it is at 60 Hz. IFs cover the range from 300 Hz to 100 kHz. The natural source of IF is the lighting discharges. Sferics are electromagnetic impulses created in Earth’s atmosphere because of the discharges. Artificial sources are induction hobs, electronic article surveillance systems, near-field communications, wireless charging of electric cars, and energy saving bulbs. Medical applications may also produce IF such as MRI, nerve stimulators, and electrosurgical devices. In industry, a possible source are the inductive heating devices and welding machines [7]. At low frequencies the wavelength is at least order of magnitude longer than the dimensions of a human body. For example, at 100 kHz the wavelength is 300m, thus 150 times longer that a human of 2 m height. For this reason, exposure to these fields induces fields and currents inside the body.

1.4.1 ELFs Interaction with Biological Tissue and Health Effects (0.1 Hz to 300 Hz)

Exposures to either electric or magnetic fields result in the induction of electric fields and associated current density in conductive tissue. The magnitudes and spatial patterns of these fields depend on the type of the exposure field (electric vs. magnetic), their characteristics (frequency, magnitude, orientation, etc.), and the size, shape, and electrical properties of the exposed body (human, animal). A biological body significantly perturbs an external electric field, and the exposure also results in an electric charge on the body surface. The external electric field is also strongly perturbed by metallic or other conductive objects.

ELF Electric field Interaction: External electric field of extremely low frequencies change/affect the surface charges by reorientation of electric dipoles already present in tissue and formation of new dipoles (bound charge polarization), creating an electric field strength on

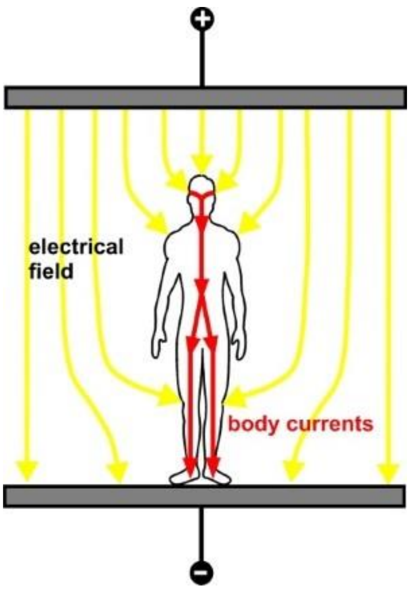

Figure 1.4. The external EF causes electrical charging on the body surface and internal body weak electric field and low body currents Source: EMF portal [8]

the body. People feel these fields due to micro-discharges and the hair movement. There is no reported direct adverse health effect of these interactions except stress due to prolonged exposure to the microshocks. Moreover, except for the surface effects, ELF electric fields induce electric field and currents inside the body. Non-uniform charges are induced on the surface of the body and the current direction inside the body is mostly vertical (Fig. 1.4).

The current densities of induced electric body currents differ, and good grounding generally increases these currents. The internal field is several hundred weaker than the external one at 50/60 Hz. The internal field cannot stimulate nerves and muscles. So, there is no health effect even from the internal electric field. A 50 MHz uniform external EF at 1 kV/m can produce internal EF of 5.72 mV/m at bones, 2.74 mV/m on the skin, 1.09 mV/m in lungs, 1.65 mV/m in muscles, based on WHO Environmental Health Criteria 238 (2007) data. Therefore, an ELF EF has an effect limited to the body surface. The relative magnitudes of these different effects depend on the electrical properties of the body. Electrical conductivity is related to the flow of electric current, and permittivity governs the magnitude of polarization effects. Electrical conductivity and permittivity vary with the type of body tissue and depend on the frequency of the applied field [5].

ELF Magnetic field Interaction: An external ELF magnetic field induces electric fields and body currents ("Eddy currents") inside the human body (see Fig. 1.5).

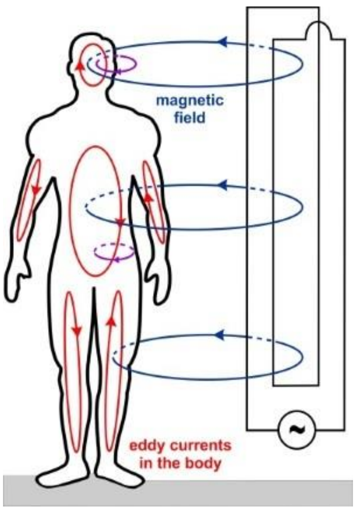

Figure 1.5. Alternating MFs cause internal Eddy currents and penetrate the human body. Source: EMF portal [8]

Human and animal bodies do not perturb the magnetic field, and the field in tissue is the same as the external field since the magnetic permeability of tissues is the same as that of air. The magnetic field (MF) produces an internal EF, according to “Faraday Low of Induction”, that varies with distance away from the center and in proportion to frequency. There is no induced EF in the center, but it reaches a maximum at the body surface. For 60 Hz uniform magnetic flux of 0.4 μT, the induced EF along the circular path subscribing the head and trunk is 9.04 and 15.07 μV/m respectively. The induced EF produces the “Eddy currents” in conductive tissues. The current’s magnitude increases with the distance from the center of the body.

$$\textbf{Current Density: } J_{internal} = \sigma * E_{internal}, \qquad (4)$$

where σ = the tissue conductivity

Electric fields and currents induced in the human body cannot be measured easily. Measurements in animals have been performed, but data are limited, and the accuracy of measurements is relatively poor.

Tissue conductivities at the power-line frequency of 60 Hz are shown in Table 1.3.

Table 1.3. Tissue conductivities at the power-line frequency of 60 Hz [1].

Tissue Type	Conductivity σ
Air	0
Fat, Bone, Cartilage,	0.04
Muscle, Intestine,	0.11
Nerve, Brain	0.12
Liver	0.13
Kidney	0.16
Spleen	0.18
Blood	0.6

The strength of the induced currents depends on the frequency, magnetic flux density, the spatial distribution (field strength at each point in space) of the magnetic field and the area of the body cross section, which is penetrated by the magnetic field. The direct effect is the perceptible stimulation of sensory receptors, nerves, and muscle cells. Internal current densities up to 10 mA/m^2 cannot lead to perceptible effects. In case of higher values, 100 mA/m^2, acute effects are expected in the central nervous as well as acute effects of the visually evoked potential. For exposure to external electric field ~100kV/m or magnetic field of 5-10 mT, at 50 Hz, irritations or impairments on the skin and eyes (phosphenes, flashes in the periphery of the visual field due to stimulation of optic nerve or the retina's nerve cells) may occur. In cases exceeding 500 mT at 50 Hz, health effects such as ventricular fibrillations, and involuntary spasmodic movements are reported due to severe skeletal muscle and heart muscle stimulation. The magnitude of the induced fields determines if the effects will be reversible (Fig. 1.6). Exposure to low-frequency electric and magnetic fields normally results in negligible energy absorption and no measurable temperature rise in the body [1].

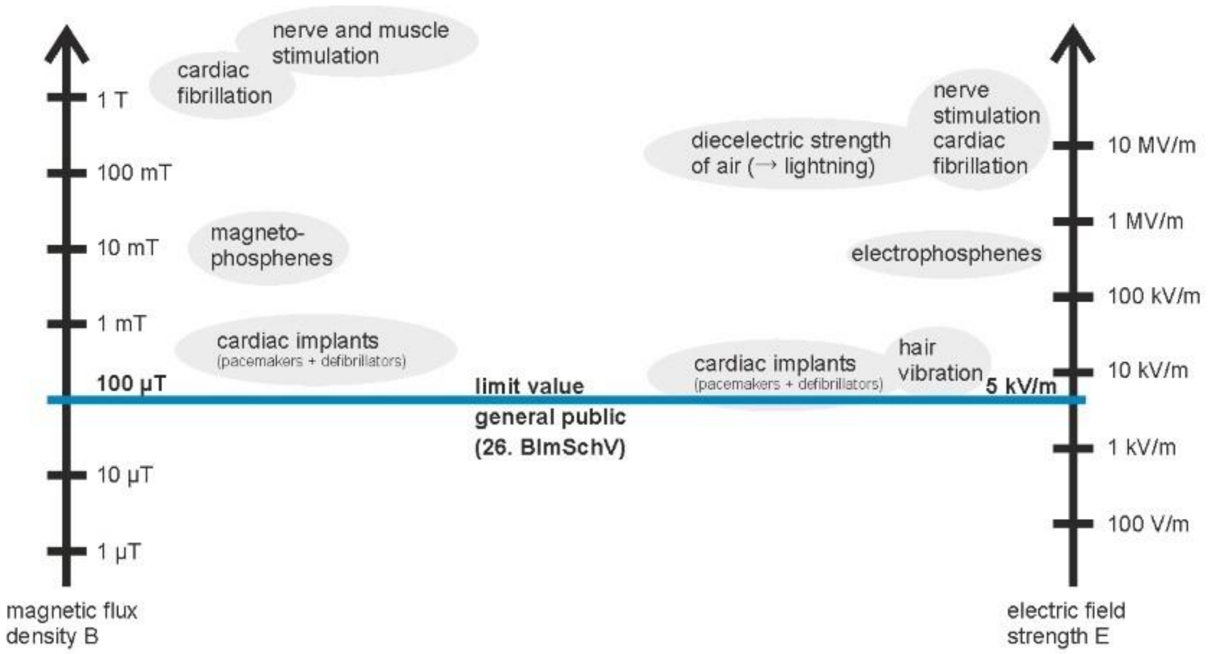

Figure 1.6. Electric field and Magnetic field thresholds at 50 Hz for perceptible effects and the reference (safety) limits based on ICNIRP 1998 guidelines. Source: EMF Portal [8].

1.4.2 IFs Interaction with Biological Tissue and Health Effects (300 kHz – 100 kHz)

The research on this band's possible health effects is limited compared to ELF. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) [9] proposes the scientific community to study these frequencies in high priority. For example, risks on pregnancy outcome should be considered from exposures due to antitheft devices in shops. These exposures may exceed the reference levels.

1.4.3 Other Health Effects and Epidemiological Studies up to 100 kHz

According to [9], there is no causal relationship between ELF and self-reported symptoms.

ELF and childhood leukemia: A possible association between ELF magnetic fields and the promotion of cancer has been examined in several epidemiological studies, 35 years ago. Two pooled analyses, [10] and [11]. reported that: “an excess risk may exist for average exposures exceeding 0.3 – 0.4 μT, although the authors of those analyses cautioned strongly that their results cannot be interpreted as showing a causal relationship between magnetic fields and childhood leukemia”. The International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) classified ELF MFs as class 2B "possibly carcinogenic to humans" [12]. There is no adequate animal model of the most common form of childhood leukemia, acute lymphoblastic leukemia. Most studies report no effect of 50–60 Hz magnetic fields on leukemia or lymphoma in rodent models. There is no evidence supporting an increase in risk or development of cancer in adults such as leukemia, breast cancer or brain tumor, according to German Commission on Radiological Protection recommendation, issued in 2008. According to ICNIRP [13]: “the overall conclusion supports that in contrast to the epidemiological evidence of an association between childhood leukemia and prolonged exposure to power frequency magnetic fields, the animal cancer data, particularly those from large-scale lifetime studies, are almost universally negative. The data from cellular studies are generally supportive of animal studies, though more equivocal”. SCENIHR 2015 [9] indicates that the previous assessment (issued in its 2009 Opinion) on a possible association between long-term exposure to ELF magnetic fields and an increased risk of childhood leukemia remains valid. Different studies, with different settings at different points in time, showed a possible association. Moreover, according to the same Opinion: “The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukemia with estimated daily average exposures above 0.3 to 0.4 μT. As stated in the previous Opinions, no mechanisms have been identified, and no support exists from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies, prevent a causal interpretation”. According to EMF Portal [14]: “Childhood leukemia is a relatively rare disease (ca. 49.000 new cases per year worldwide, in Germany ca. 600 new cases per year). The risk factors of childhood leukemia are largely unknown. Residential exposure to more than 0.3 μT magnetic flux densities is also very rare (applies only to 1-4% of children). External exposure sources (e.g., high-voltage power lines) contribute one-third to the residential exposure, and sources at home like household appliances add two-thirds to the residential exposure”. The European community project ARIMMORA (Advanced Research on Interaction Mechanisms of electromagnetic exposures with Organisms for Risk Assessment), which is supported by the 7th Research Framework Program of the European Commission, concludes that [15]: “In ARIMMORA for the first time, a transgenic mouse model was used to mimic the most common childhood leukemia: new pathogenic mechanisms were indicated, but more data are needed to draw definitive conclusions. Although experiments in different animal strains showed exposure-related decreases of CD8+ T-cells, a role in carcinogenesis must be further established. No direct damage of DNA by exposure was observed. Overall, in the literature, there is limited evidence of carcinogenicity in humans and inadequate evidence of carcinogenicity in experimental animals, with only weak supporting evidence from mechanistic studies. New exposure data from ARIMMORA confirmed that if the association is causal, up to 2% of childhood leukemias in Europe, as previously estimated, may be attributable to ELF-

MF. In summary, ARIMMORA concludes that the relationship between ELF-MF and childhood leukemia is consistent with possible human carcinogenicity".

Other related health effects [9]: According to experimental studies, short-term and/or long-term exposure to ELFs is unlikely to cause dangerous cardiovascular effects, as reported in WHO Environmental Health Criteria 238. Moreover, epidemiological studies provide no evidence of an association between ELFs (EF or MF) and cardiovascular diseases [16]. Studies related to possible effects of ELF and the waking EEG are heterogeneous considering the magnitude of the fields, the exposure duration, and the statistical methodology to drive a sound conclusion. Behavioral outcomes and cortical excitability are also not conclusive. Epidemiological studies on neurodegenerative diseases, including dementia, do not lead to an increased risk associated with ELF MF exposure. ICNIRP 2010 [13] confirms that exposure to 50-60 Hz ELFs has no adverse effects on the neuroendocrine system and melatonin secretion. Moreover, no evidence for adverse pregnancy outcomes exists due to ELF MF. Maternal residential ELF MF exposure during pregnancy and their children's health exhibit severe methodological issues that must be addressed. Implausible effects are reported and need to be replicated independently before any risk assessment result is concluded. Finally, the reproductive function in humans is not affected by ELF MFs.

1.4.4 Legislation and Safety Limits

Basic restrictions refer to values of the internal induced fields that should not be exceeded. These fields cannot be evaluated in the daily routine. For that reason, reference levels have been adopted, which refer to the values of the external fields (measurements performed in the air by experts' laboratories). Electric field strength and magnetic field strength are measured in the air Between 1 Hz and 10 MHz; basic restrictions are provided on current density to prevent effects on nervous system functions. ICNIRP 1998 and 2010 guidelines are valid:

- International Commission on Non-Ionizing Radiation Protection (ICNIRP). 1998.

Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74:494–522.

- International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2010. FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1HZ – 100 kHz). Health Phys 99(6):818-836

In Greece, 1998 guidelines were adopted (see below Table 1.4), and no changed after the ICNIRP 2010 update

Table 1.4. ICNIRP 1998 Basic Restrictions and Reference Levels

Basic Restrictions 1998:

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	$40/f$	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	$f/100$	—	—	—
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	$8/f$	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	$f/500$	—	—	—

Reference Levels 1998 for occupational exposure:

Frequency range	E-field strength (V m^{-1})	H-field strength (A m^{-1})	B-field (μT)	Equivalent plane wave power density S_{eq} (W m^{-2})
up to 1 Hz	—	1.63×10^5	2×10^5	—
1–8 Hz	20,000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$	—
8–25 Hz	20,000	$2 \times 10^4/f$	$2.5 \times 10^4/f$	—
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	—
0.82–65 kHz	610	24.4	30.7	—
0.065–1 MHz	610	$1.6/f$	$2.0/f$	—

Reference Levels 1998 for general public exposure:

Frequency range	E-field strength (V m^{-1})	H-field strength (A m^{-1})	B-field (μT)	Equivalent plane wave power density S_{eq} (W m^{-2})
up to 1 Hz	—	3.2×10^4	4×10^4	—
1–8 Hz	10,000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	—
8–25 Hz	10,000	$4{,}000/f$	$5{,}000/f$	—
0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	—
0.8–3 kHz	$250/f$	5	6.25	—
3–150 kHz	87	5	6.25	—
0.15–1 MHz	87	$0.73/f$	$0.92/f$	—

1.4.5 ELFs and Pacemakers' (PMs) Possible Interference

According to Korpinen's [17] and [18] studies, PM does not interfere with EF and MF strengths met in the public's daily life. Only the fields created under 400 kV power lines could interact with the operation of PMs. PM tests in France indicated no interference in MF levels below 100 μT, which is the Reference level adopted in Greece. The European Committee for Electrotechnical Standardization [19] and [20] issued standards on implantable medical devices. Based on the European Norm 50527-1, MFs of 100 μT is the 'safety level' for PMs.

1.5 Radiofrequencies (RFs): 100 kHz to 300 GHz

1.5.1 Introduction

RF fields cover the spectrum range from 100 kHz to 300 GHz according to the latest ICNIRP 2020 guidelines [3]. Above 3 GHz, the fields are called microwaves (MWs), and above 30 GHz, the fields are also called millimeter Waves (mmWaves or MMW). Natural sources of radio waves are the sun and the cosmic background radiation that travels from the big bang. In earth's environment, the strength levels of those fields are low compared to our daily environment exposure. Man-made RF fields include wireless communications transmitting information (Radio FM, TV broadcast, Mobile Communications, Wi-Fi, Radars, and therapeutic/diagnostic applications). Mobile communications are operating under a Radio Base Stations (RBS) network using directive antennas to cover an area and a number of subscribers. According to the technology and the frequency used by these antennas, the area covered by an RBS range from a few meters to 30 km. The frequencies used for mobile communications range from 700 to 3500 MHz. RBS antennas do not radiate in all directions, their beams are directive focusing on a sector (see Fig. 1.7). Main beam is emitted in front of the antenna panel as a lobe of a specific angle opening. Main beam is responsible for the largest part of the human RF exposure, creating an electromagnetic field of higher strength than the side lobes (beams). EF (E) and MF

(H) are combined to an EMF, and the Power Density S (power per unit area, W/m^2) is the physical quantity of its strength (quantity of measuring the exposure). EF and MF can also be measured separately in V/m and A/m respectively. In the far-field region, the plane-wave model is a good approximation of the electromagnetic field propagation. The characteristics of a plane wave are: The E and H vectors and the direction of propagation are mutually perpendicular, the phase of the E and H fields is the same, and in free space, the ratio of their amplitudes E/H = 377 ohm is constant, which is the characteristic impedance of free space. At the near field region, the situation is more complicated because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation. In the near field, the EMF is inhomogeneous, and there may be substantial variations from the plane-wave impedance of 377 ohms. We may find almost pure E fields in some regions and almost pure H fields in others.

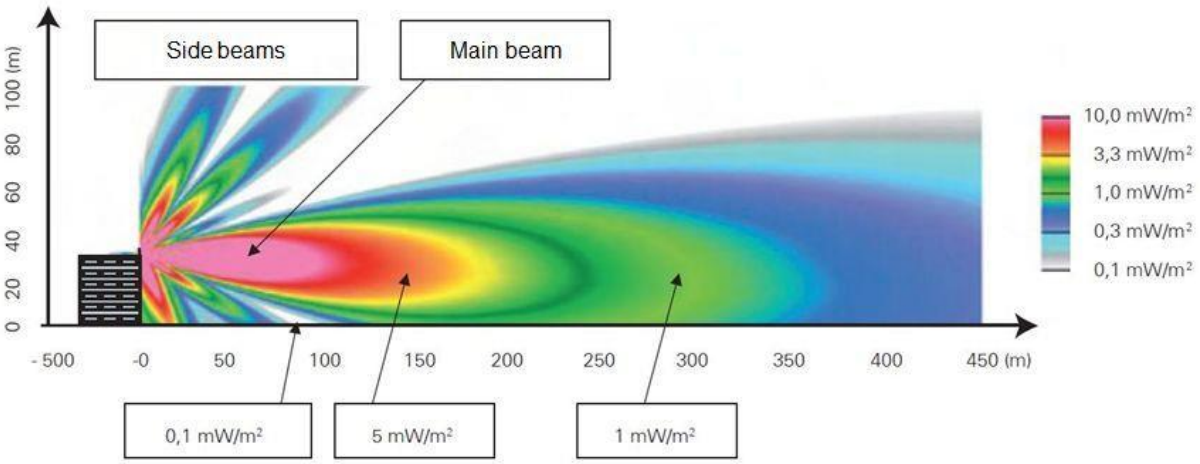

Figure 1.7. Distribution of the RF emission from RBS antenna in the vertical pattern. Non uniform EMF is created with the most part of the radiation emitted from the main beam at the front of the antenna. Source of Figure: EMF Portal [21].

According to EMF theory [5], the three quantities are related as in Eq. (5):

$$S = E \, x \, H = \frac{E^2}{377} \qquad (5)$$

In practice Power Density (S) depends on the antenna characteristics, such as power and gain. Of course, it is also dependent on the distance from the source (antenna) following the inverse square low (radiation decreases with the distance increase). The following equation (6) describes the power density of an RF field at a distance R from the antenna, where P is the output power of the antenna (Watt), G is the gain of the antenna (dBi), and u is the reflector coefficient (effect of the filed reflection in surfaces)

$$S = \frac{P * 10^{0.1G}}{4\pi R^2} * u^2 \qquad (6)$$

The Specific Absorption Rate (SAR)

RF radiation has the capability to penetrate the body, thus it can be absorbed. SAR is the measure of the energy deposited in the body (Watt per kg of tissue – W/kg), expressed in equation (7). It is the right quantity to use to assess the absorption of energy (thus the interaction effect) in the human body for frequencies between 100 kHz to 10 GHz. For higher frequencies, as the absorption occurs at the body surface (skin), the Power Density is used. Under that concept Basic Restrictions are formed.

$$SAR = \frac{\sigma * E^2}{\rho} \qquad (7)$$

where, σ = conductivity, E = Electric Field (RMS value), and ρ = mass density

Some rules of thumb for the SAR assessment are presented in [1]:

- Wetter materials (muscle, high-water content tissues) are generally more lossy than drier materials (fat, bone) and absorb more energy from electromagnetic fields.
- The SAR is higher when the incident E-field is more parallel to the body than perpendicular to it.
- The SAR is higher when the cross-section of the body perpendicular to the incident H-field is larger than when the section is smaller.

- Sharp corners, points, and edges concentrate E-fields. When placed perpendicular to E-fields, conducting wires and plates cause minimum perturbation to the fields; when placed parallel to them, maximum perturbation.
- A uniform incident field does not generally produce a uniform internal field.
- Depth of penetration decreases as conductivity increases, also as frequency increases (see also par. 1.5.2).
- Objects small compared to a wavelength cause little perturbation and/or scattering of electromagnetic fields.
- Below resonance, the SAR varies approximately as f^2
- For E polarization, SAR increases faster than f^2 just below resonance; just beyond resonance, SAR decreases approximately as 1/f and then levels off. Variation of SAR with frequency is most rapid near resonance.
- Near resonance and below, SAR is greatest for E polarization, least for H polarization, and intermediate for K polarization.
- For E polarization, the SAR increases as an object becomes longer and thinner and decreases as an object gets shorter and fatter.

1.5.2 RF Interaction with Biological Tissue

Penetration of RF field in the body

The electric properties of the tissue, e.g., conductivity and permittivity, are determined by the tissue composition. The distribution of water molecules, ions, and other molecules determines the conductivity value. A higher conductivity, due to a higher water or salt content, increases the interaction of the field with the tissue and, thus, the thermal effect. Conductivity is a measure of the field attenuation, hence the conversion of energy into heat in the tissue. This attenuation occurs as the “conduction” destroys the electromagnetic radiation because the free electrons and ions of the material are moved by the incoming field. The free electrons and ions seek the lowest energy level and rearrange themselves in such a way as to block the entrance of the field. Free electrons and ions lose energy due to collisions with each other, causing the electromagnetic energy to be dissipated by the collisions and converted into heat. The relative penetration depth (δ) is defined as the point in the tissue at which an electromagnetic field reaches only approximately 37% of its output amplitude (equation 8). Skin depth penetration depends on permittivity and conductivity values. The penetration in the body decreases as the conductivity and thermal effect increases.

$$\delta = (\frac{1}{\omega})\left\{\left(\frac{\mu\varepsilon}{2}\right)\left[\left(1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right)^{1/2} - 1\right]\right\}^{-1/2} \qquad (8)$$

The tissue heating does not increase steadily from the outside to the inside of the body. There are areas in the body with higher local heating (hot spots), and areas with lower heating effect. Bone and fatty tissue, for example, exhibit lower conductivity (because of their low water content), so they are less capable of absorbing energy, they are heated less, and the penetration depth is higher. On the contrary, muscle tissue is a good conductor; the energy absorption is high and is converted into heat most efficiently. Then, the penetration depth is lower. The depth of penetration is associated with the thermal effect. It is higher in brain, fat, and bone tissues than in muscle tissue (see Fig. 1.8 based on EMF portal [22]), as muscle tissue absorbs the field

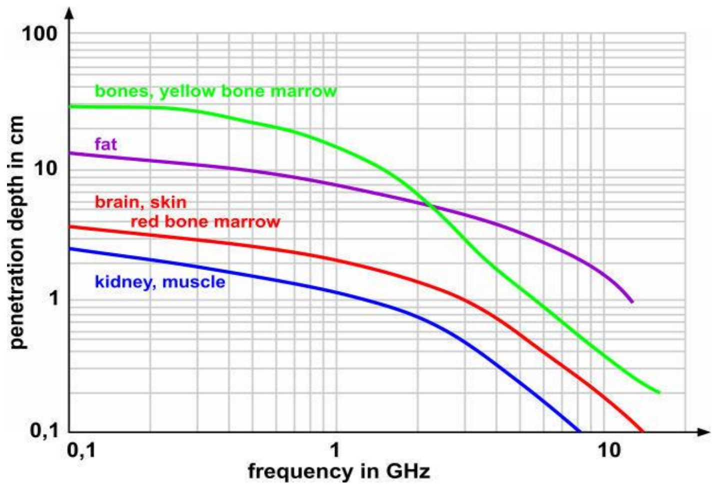

Figure 1.8: Penetration depth VS Frequency for different kind of tissues. Source: EMF portal [22]

to a greater extent and thus the field energy is converted into heat most efficiently.

The average depth of penetration of fields in muscle tissue is, for example 1.5 cm at 0.5 GHz and 0.5 cm at 2.5 GHz band (used in mobile communication and microwave ovens), and above 10 GHz, it is only about 0.2 mm and less.

In the following Table 1.5, Conductivity (σ) values for different RF frequencies and tissues are presented with the skin penetration depth (δ) for each case. Conductivity data based on Gabriel et al., 1996 [25].

Table 1.5. Low and high-water content tissue VS frequency and skin depth penetration

	Low water content				**High water content**			
	Fat		**Bone**		**Muscle**		**Skin**	
Frequency	**σ (S/m)**	**δ (mm)**	**σ**	**δ (mm)**	**σ**	**δ (mm)**	**σ**	**δ (mm)**
150 MHz	0.04	366.1	0.07	301.0	0.7	67.2	0.5	85.0
450 MHz	0.04	301.9	0.10	202.2	0.8	51.3	0.7	52.9
835 MHz	0.05	252.0	0.14	139.5	0.9	43.5	0.8	41.5
1.8 GHz	0.08	157.1	0.28	66.7	1.3	29.2	1.2	28.3
2.45 GHz	0.10	117.1	0.39	45.8	1.7	22.3	1.5	22.6
3 GHz	0.13	93.6	0.51	35.2	2.1	18.0	1.7	18.9
5 GHz	0.24	49.4	0.96	17.7	4.0	9.3	3.1	10.5
10 GHz	0.58	19.6	2.13	7.3	10.6	3.3	8.01	3.8

In the following Table 1.6, the penetration depth for a cylindrical model of man and the approx. percentage of total body mass (in humans) that might be exposed as a function of radiation frequency are presented by Durney et al.,1986 [1].

Table 1.6. Penetration depth and the approx. percentage of total body mass (in humans)

Frequency (GHz)	Penetration (cm)	% Total Body
1	4.05	20.8
2	2.46	15.6
4	1.66	9.2
8	0.65	4.0
10	0.46	2.9
20	0.16	1.0

ICNIRP 2020 [3] new safety guidelines also provide a table with RF penetration for frequency above 6 GHz related to the electrical permittivity and conductivity values (Table 1.7).

Table 1.7. RF penetration for frequency above 6 GHz related to the electrical permittivity and conductivity values.

Frequency (GHz)	Relative Permittivity	Conductivity (S/m)	Penetration depth (mm)
6	36	4.0	8.1
10	33	7.9	3.9
30	18	27	0.92
60	10	40	0.49
100	7.3	46	0.35
300	5.0	55	0.23

Absorption of RF field in the body

The RF absorption capability of the whole body is frequency dependent. For adults, the maximum absorption occurs between 30 and 100 MHz, around 80 MHz (see Fig. 1.9). At that point, the body dimensions and the wavelength of the field are of the same order of magnitude. The body height matches the half of the wavelength. Thus, for a body height of 1.80 m, absorption resonance occurs at 83.3 MHz fields with a wavelength of 3.60 m. Moreover, the posture also influences the resonance point (e.g., standing, sitting, arms stretched). As a result, children with smaller sizes exhibit resonance at higher frequency that the adults (e.g., the maximum absorption for 1.00 m body height is at 150 MHz). Resonance occurs at 600 MHz for the rat. At close distance to RF sources (for example mobile phone and head), with frequencies of approximately 300 MHz and higher, absorption occurs only in parts of the body (partial body absorption) because of the decreasing wavelengths at these frequencies compared to the body dimensions and the proximity of the transmitter. Still, if the field source at such frequencies is far away, a small fraction of the transmitted energy is absorbed by the whole body. Therefore, the higher the frequency the shorter the distance the field can penetrate the body. According to Durney et al., 1986 [1] the spectrum can be divided into 4 regions (Fig. 1.9).

- from about 100 kHz to less than 20 MHz: absorption in the trunk decreases rapidly with decreasing frequency, and significant absorption may occur in the neck and legs.
- from about 20 MHz to 300 MHz: high absorption in the whole body, resonance effects.
- from about 300 MHz to several GHz: significant local, nonuniform absorption occurs.
- above 10 GHz: energy absorption occurs primarily at the body surface.

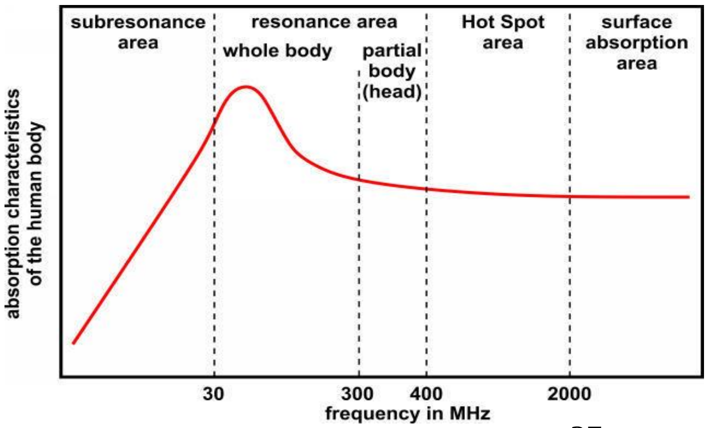

Figure 1.9. Energy Absorption VS Frequency (resonance effect for adult at 80 MHz for 1.80 m height). Source: EMF portal [22]

The Millimeter wave case

Millimeter wave (mmWave) radiation covers the spectrum above 30 GHz to 300 GHz with wavelength ranging from 1 mm to 1 cm, and a photon energy between 10^{-3} and 10^{-4} eV (Fig. 1.10).

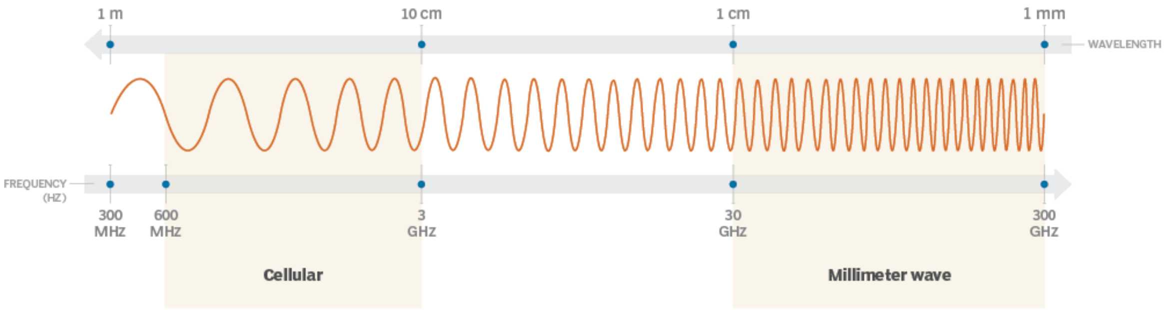

Fig. 1.10. Cellular VS mmWave spectrum in 5G.

Source: https://www.techtarget.com/searchnetworking/definition/millimeter-wave-MM-wave

This level of energy is several orders of magnitude below the ionizing threshold (above 10 eV). This means that the mmWave radiation is not able to break ionic, hydrogen or van der Waals bonds present in cells. Non-ionizing RF radiation may induce rotation of dipoles. Thus, can induce heating of biological tissue. Thermal effects appear at exposure levels above 50 – 100 W/m^2 (we may recall that the ICNIRP 1998 and 2020 reference level for the general public at mmWave bands is 10 W/m^2). According to LeDrean's [23], high-intensity mmWaves exhibit an impact on skin and cornea in a dose-dependent manner. Heating sensation is reported at low-power densities. Pain follows at higher exposures, while severe physical damage can occur at very high powers. People exposed to high-power 94-GHz radiation undergo a sudden increase in their superficial temperature, resulting in a quick burning sensation and in an escape reaction from the mmWave beam. Human volunteers reported pain sensation with an increase in surface temperature. Elevation of temperature induces health effects at the cellular level such as cell growth, cell morphology, and cell metabolism. It can also induce the production of reactive oxygen species and increase DNA, lipid, and protein damage. All these parameters have often been highlighted in studies assessing the biological effects of electromagnetic fields. Body temperature between 40 and 44 ^{0}C is not lethal to most mammalian cells, but it can activate an adaptive mechanism called heat-shock response (HSR). During HSR, cells synthesize many proteins involved in protection and cell survival. Among these proteins, the heat-shock protein 70 (HSP70) is dramatically over-expressed. This factor is therefore used as a convenient biomarker to monitor the impact of environmental factors on cells. Because acute HSR is not observed below 39 ^{0}C, the scientific community often considers that moderate elevation of temperature ($T < 2\ ^{0}$C) has no significant consequence for the cell. Thermal effects are excluded as the networks operate in compliance with the current ICNIRP 1998 and 2020 safety guidelines. We should focus on the non-thermal effects. There are many studies covering the issue. Biological effects are dependent on the power density, the exposure duration, and the cell type. Thus, it is very difficult for the scientific community to ensure repeatability and consistency. Biological and environmental factors also impact in vivo and in vitro studied. Consequently, heterogenicity of the published data appeared. Millimeter waves exhibit shallow penetration into biological tissue. GSMA presented the correlation between skin depth penetration and mmWave frequency in the following Fig. 1.11 (ITU 2019 conference).

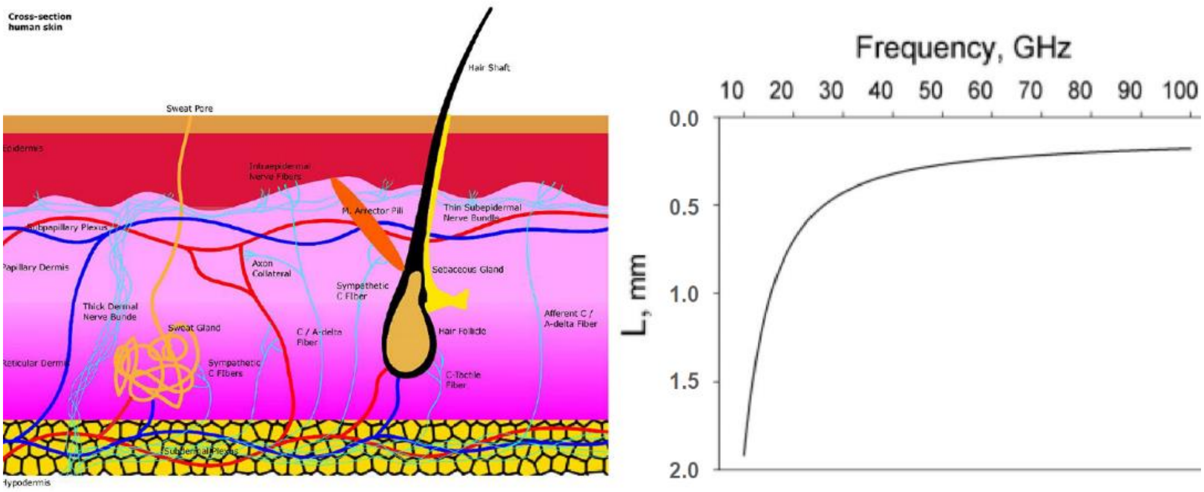

Figure 1.11. (Glatte et al., 2019) skin layers imaging. Penetration in the skin according to the frequency applied (GSMA, ITU conference 2019)

According to Zhadopov's 2011 study [24] and 60 GHz incident power, almost 30 to 50 % of the radiation is reflected from the skin. Transmitted power decreases exponentially in the skin as a function of depth. Almost 40% (for Gabriel [25] and Gandhi [26] models) and 60% (for Hwang model [27]) of the incident power reach dermis; only 0.1% (for Gabriel and Gandhi models) and 10% (for Hwang model) reach the fat layer. These results suggest that only epidermis and dermis should be considered in health effects. One may wonder how radiation with such a shallow penetration into the body can have biological effects at the level of the whole organism. However, it should be noted that skin is not isolated from the rest of the body, and this organ contains capillaries and nerve endings. It is possible that mmWave bio-effects could be transmitted through secreted molecular factors by the skin or through the nervous system.

Millimeter wave fields have been also used in medical therapy. Three frequencies are commonly employed in therapy: 42.2, 53.6, and 61.2 GHz. The choice of these frequencies was empirical, but it is possible that the penetration depth of these waves is involved. This allows us to target a precise subpopulation of cells in the skin. The therapeutic electromagnetic waves are of a low intensity. It's a non-invasive method that uses non-ionizing microwaves locally on the skin. It aims to ameliorate many different issues, from pain to cardiovascular problems to diabetic polyneuropathy. It's more used as a complementary therapy that can help relieve some of the issues these diseases can create. With that in mind, here's a list of issues that millimeter wave therapy might help address: pain relief, wound healing, side-effects of chemotherapy, dermatitis, diabetes, and cardiovascular problems. More information on mmWave and medical therapy are presented in paragraph 6.3.

1.5.3 Thermal Health Effect from RF Radiation

Thermal effects (tissue heating) are the main possible effects on humans and biological systems. They are caused by the periodical movement stimulation of dipole molecules and charge carriers, which can move and rotate freely (e.g., water molecules in water, body fluids or tissues containing water). The external field exerts forces on charged groups of the dipole molecules and charge carriers resulting in a torque affecting the whole molecules and causing the charge carriers to rotate. Heat is generated by friction between rotating molecules and/or moving charge carriers of other atoms. The frequency and the strength of the field, as well as the composition of the tissue in the body, play an essential role regarding the amount of energy which is absorbed and is converted (or not) to heat. Hirata et al., 2007 paper [28], concludes that a naked body exposed to 65 MHz and 2 GHz EMF, for at least 60 min, increases in both cases its temperature by 1℃ for a whole-body SAR value of 6 to 8 W/kg (normal persons in good health state for normal ambient conditions 28℃). The time needed to reach the steady state temperature rise depends also on the individual sweating rate. Thus, for EMFs below 6 GHz, a period of 30 min or longer is needed for this effect. For RF fields above 6 GHz the interaction is limited to the surface tissues. For conservative reasons, ICNIRP 2020 [3] does not change the time needed to reach this steady state temperature rise. According to Hirata [28], an exposure of 4.5 W/kg is sufficient to produce the same effect (+1℃ rise) to a person of low sweat rate (elderly persons). Smaller-dimension bodies (children) need greater whole-body SAR to reach the same temperature increase as an adult.

1.5.4 Other Health Effects and Epidemiological Studies up to 300 GHz

Following the analysis of the thermal effect due to the absorption of RF frequency by the human body, we focus now on the non-thermal possible effects that are reported in the international bibliography for RF exposure levels below the adopted guidelines. According to ICNIRP 2020 [3] guidelines and the final Opinion of SCHEER 2023 [29], we summarize the current scientific knowledge for possible health effects due to RF exposure.

- Brain physiology and function: The scientific knowledge based on experimental or epidemiological evidence confirms that exposure to radiofrequency EMFs does not affect higher cognitive functions relevant to health.

- Auditory, Vestibular, and Ocular function: No effects on auditory, vestibular, or ocular function or pathology that may lead to adverse health effects have been confirmed. Superficial eye damage has been reported in rabbits at exposures close to 1.4 kW / m^2, but no relation with humans has been substantiated.

- Neuroendocrine System: Very few epidemiological studies reported effects on melatonin levels, but the results were not confirmed. No consistent evidence has been concluded. Effects in rodents have been reported at exposures of 4 W/kg (above the safety limits adopted). No evidence for other hormones.

- Neurodegenerative diseases: According to a Danish epidemiological cohort study on the potential effects of mobile phone use on neurodegenerative disorders concluded a reduced risk of Alzheimer's disease, vascular and other dementia, and Parkinson’s disease (ICNIRP, 2020). These results may have been derived from reverse causation: prodromal symptoms of the disease may prevent persons with early symptoms to start using a mobile phone. Moreover, there are no human experimental studies. The increased risk reported in rats was not confirmed by other studies. No adverse effects on neurodegenerative diseases have been substantiated.

- Cardiovascular system, Autonomic Nervous System, and Thermoregulation: Considerable body heating can affect the cardiovascular system and lead to health effects. By complying to ICNIRP limits (1998 and 2020 guidelines), there is no possibility for a temperature rise to occur. Few epidemiological studies are available and do not conclude an association between RF exposure and cardiovascular health. In animals, under very high whole-body exposures of 4 W/kg, health effects have been recorded. In general public, the Basic Restriction is at 0.08 W/kg for whole-body exposure.

- Immune System and Hematology: Few studies have been carried out. No evidence that there is health effect from RF fields in the immune system or hematology.

- Fertility, Reproduction, and Childhood Development: Temperature increase may lead to effects on female or mail reproduction system including embryo or fetal losses, malformations, and abnormalities. There are studies that support this at exposures below the critical value of 4 W/kg, but these studies have severe methodological limitation (like design, exposure assessment). In daily life such exposures close to 4 W/kg cannot be achieved. Moreover, maternal phone use during pregnancy has been investigated with no adverse result on child cognitive or psychomotor development and milestones delays.

- Cancer: Two recent studies based on animals have announced their results: the U.S. National Toxicology Program- NTP study, and Ramazzini Institute study in Italy. Even they concluded effects or the rats and mice, the studies suffered from severe inconsistencies on the levels of exposure used (too high for NTP, high for Ramazzini) or the statistical method followed. Moreover, no consistency was seen across these two studies. Male rats in NTP showed severe malignant Schwannoma of their heart, a result that was not appeared in females. Concerning the epidemiology, a considerable number of studies on brain tumors, acoustic neuroma, parotid gland tumor and other types (such as leukemia, lymphoma, uveal melanoma, pituitary gland tumors, testicular cancer, and malignant melanoma) is published. The only study available on mobile phone use in children and brain tumor risk showed no increased risk of brain tumors. Studies on human exposure from radio and television sources did not conclude an increased risk either in children or in adults. According to ICNIRP 2020 [3] no effects of RF on the induction and/or development of cancer can be substantiated.

A more detailed approach on 5G new technology (new antennas used, new spectrum bands utilized) impact on human health will be presented in the chapter dedicated to 5G.

1.5.5 Legislation and Safety Limits (ICNIRP, 2020)

As mentioned in ELFs, Basic Restrictions are the safety limits referring to the physical quantity present inside the body. In ELFs these restrictions referred to the internal currents and fields. For RFs fields the **Basic Restriction** (Table 1.8) refers to the absorbed energy in the body which will be converted (or not) to heat. The absorbed energy is described by the whole-body or the local SAR (Specific Absorption rate). As discussed in 1.5.3 the SAR value where a whole-body temperature rise of 1℃ occurs is the 4.5 W/kg for persons with low sweating rate (elderly). Thus, ICNIRP 2020 confirms that the existing (issued in 1998) whole-body SAR limit is valid (4.0 W/kg are accepted) averaging in a 30-min interval. A reduction factor of 10 (SAR = 0.4 W/kg) is applied for occupational exposure, to account for scientific uncertainty, variability in environmental conditions, and the individual character of human physiology and physical activities level. Age, health status and other factors are included in this conservative approach. Concerning the general public, the reduction factor is 50 due to its unawareness of the exposure risks (SAR = 0.08 W/kg). **Reference levels** (Table 1.9) are the safety limits applied to quantities of the external field: E (V/m) and H (A/m). These quantities are easy to be measured with portable spectrum analyzers.

Table 1.8. Basic Restrictions for whole body absorption averaging over 30 min interval and local absorption for > 6 min interval from 100 kHz to 300 GHz

Exposure scenario	Frequency range	Whole-body average SAR (W kg^{-1})	Local Head/Torso SAR (W kg^{-1})	Local Limb SAR (W kg^{-1})	Local S_{ab} (W m^{-2})
Occupational	100 kHz to 6 GHz	0.4	10	20	NA
	>6 to 300 GHz	0.4	NA	NA	100
General public	100 kHz to 6 GHz	0.08	2	4	NA
	>6 to 300 GHz	0.08	NA	NA	20

Table 1.9. Reference Levels for exposure from 100 kHz to 300 GHz averaging over 30 min

Exposure scenario	Frequency range	Incident E-field strength; E_{inc} (V m^{-1})	Incident H-field strength; H_{inc} (A m^{-1})	Incident power density; S_{inc} (W m^{-2})
Occupational	0.1 – 30 MHz	$660/f_M^{0.7}$	$4.9/f_M$	NA
	>30 – 400 MHz	61	0.16	10
	>400 – 2000 MHz	$3f_M^{0.5}$	$0.008f_M^{0.5}$	$f_M/40$
	>2 – 300 GHz	NA	NA	50
General public	0.1 – 30 MHz	$300/f_M^{0.7}$	$2.2/f_M$	NA
	>30 – 400 MHz	27.7	0.073	2
	>400 – 2000 MHz	$1.375f_M^{0.5}$	$0.0037f_M^{0.5}$	$f_M/200$
	>2 – 300 GHz	NA	NA	10

1.6 Combined EMF Exposure (multiple fields)

As discussed, non-ionizing exposure includes different bands with different services and applications. Starting from the static fields, the EMFs end to microwaves and mmWaves. Different frequency bands interact differently with the tissue, causing different biological and / or health effects. Studying the effects from multiple exposures is of great scientific interest. Few studies have been published. Most of them exploit the MRI diagnostic tests environment during which multiple fields are created and intersect with the patients or the workers. It seems that there is no increased risk of adverse health effects from combined EMFs exposure. But further studies are needed on DNA integrity and MRI exposure [9]. Different parts of EM fields are present in MRI suites: The magnetic static field, switch gradient low LF fields (kHz), and RF fields. Exposure assessment is very difficult as mentioned in Mattsson et al., 2018 editorial article [30]. Except the different EMFs, chemicals' exposure is also added, even ionizing radiation (PET scans). Most of the studies based on animals have been performed using single frequencies and intensities. In real life, the environment is complex. A lot of frequencies of different intensities are present. A study with a real environment design has an important prerequisite. A known mechanism under which the multiple fields could lead to a carcinogenic hazard. The understanding of such a mechanism could also improve the design of the study. For example, it could indicate which fields should be selected to be tested beyond the dominant exposure from use of a mobile phone. As a result, priority for research at this time cannot be given, according to Sienkiewicz et al., 2017 publication [31].

PART TWO: MAIN BODY

Chapter 2: Low Frequency Exposure in Greece (LF)

Low frequency electromagnetic fields (LF) are a common source of exposure in human everyday life covering the range from 1 Hz to 400 kHz. Power distribution lines, transformers, household electrical appliances, power supplies, mobile devices chargers, medical exams contribute to a 24-hr exposure for adults and children. In the scientific literature, this frequency band is split into two main ranges, namely Extremely Low Frequency (ELF) with frequencies up to 300 Hz, and Intermediate Frequency (IF) with frequencies between 300 Hz above. At the 1st session of this chapter, we present an extended study of LF exposure in outdoor environments mainly derived from power distribution lines in urban, suburban, and at the vicinity of power lines environment. In paragraph 2.2 session, we present the human exposure in households derived from the main electric sources met in houses.

2.1 Outdoor Exposure

2.1.1 Introduction

During this Ph.D. work, we performed LF (mainly ELF) measurements from 1 Hz to 400 kHz, in the frame of the National EMF Research Program (EDBM34). Human exposure from ELF sources mainly derives from electric power appliances in households' environment and the power distribution outdoors. Outdoor power distribution includes a) 400 kV, 150 kV and 66 kV Overhead Transmission Lines, b) substations of 150 / 20 kV, and c) 400 / 150 kV Ultra-High Voltage Substations. The High Voltage Centers in the Transmission System operate as energy nodes interconnecting the 400 kV Transmission System with the 150 kV System and ensuring the reliability and stability of the System. The voltage is stepped up in substations connecting Generating Stations to the levels of 400 kV and 150 kV and stepped down in substations connecting to the Electricity Distribution Network.

2.1.2 Method and Material

Spectrum Analyzer

The 3-axial isotropic portable meter EHP-50F and the read-out unit NBM – 550 (manufactured by Narda Safety Test Solutions GmbH, Pfullingen, Germany) were used.

Main Unit:

The Narda Broadband Field Meter NBM-550 is one of the NBM-500 range of instruments. It measures non-ionizing radiation to the highest accuracy. With its measuring probes for electric and magnetic field strength, it covers all frequencies ranging from a few Hertz for industrial applications, through to long waves and on up to microwaves. The NBM-550 enables precision measurements for human safety to be made, particularly in the workplace environment where high electric or magnetic field strengths may be expected.

Detection Antenna (probe):

EHP-50F is a low frequency electric and magnetic isotropic field probe analyzer. It provides an advanced technology solution for field analysis in the 1 Hz to 400 kHz frequency range in an extremely high dynamic range. It includes X, Y and Z axes simultaneous measurements with a powerful, built-in, spectrum analyzer. EHP-50F can be used either connected to NBM-550 portable field meter or PC. Electric or Magnetic field is picked up by three sensors on the X, Y and Z orthogonal axes. A Digital/Analog conversion follows which transforms the signal into numeric information processed by a Digital Signal Processing unit. The magnetic sensor system is composed of three magnetic loops positioned orthogonal each other. The electric sensor system is composed of three orthogonal parallel capacitors installed on opposite side of the magnetic loops. The detection range of the probe is: 0.3 nT-100 μT (for low range), 30 nT-10 μT (for high range), 5 mV/m-1 kV/m (for low range), and 500 mV/m-100 kV/m (for high range). Harmonic and spectrum analysis are provided.

Weighted Peak method and Max Hold Mode:

According to ICNIRP 2010 [13] the total Exposure Index (EI) should be calculated considering all the frequency bands present in the environment. The result should be less than 1. (EI = sum of all MF or EF strength ratios compared to the specific limit for each frequency band).

For the magnetic field:

$$EI\ (magnetic\ field) = \sum_{j=1\ Hz}^{10\ MHz} \frac{H_j}{H_{R,j}} \leq 1$$

where H_j is the MF strength at frequency j and H_{Rj} is the reference level at frequency j.

Moreover, for the electric field:

$$EI\ (electric\ field) = \sum_{j=1\ Hz}^{10\ MHz} \frac{E_j}{E_{R,j}} \leq 1$$

where E_j is the EF strength at frequency j and E_{Rj} is the reference level at frequency j.

Weighted Peak Method (WPM) is used to assess for safety limits compliance, which also accounts for electromagnetic wave phases. Based on the WPM, the Exposure Index (EI) is calculated. EI is expressed mathematically as:

$$Exposure\ Index\ (EI) = \left| \sum_i \frac{A_i}{EL_i} \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1$$

where t is time and ELi is the exposure limit at the i^{th} harmonic frequency fi and Ai, θi, φi, are the amplitudes of the field, phase angles of the field and phase angles of the filter at the harmonic frequencies. Considering the phases, a much more realistic result is provided. The EI is given as a percentage of the maximum permissible exposure (100% of the limit). According to ICNIRP 1998 [5], the safety limit is 100 μT. It is worth noting that ICNIRP 2010 [13] updated guidelines increased the safety value to 200 μT (Greek legislation did not implement the new limit). The whole spectrum analyzer frequency range 1 to 400 kHz is considered for the WPM.

Max Hold Mode: Using the "Max Hold" mode, the maximum field strength value of each frequency step is retained and displayed. The reason for using Max Hold (thus the highest values recorded) is the "conservative approach". For the frequencies under consideration, external electric field (of the order of kV/m) could impose internal fields of the order of mV/m, based on Gourzoulidis et. al., 2016 [32]. That internal field stimulates the central nervous system (CNS) and/or the peripheral nervous system (PNS). The conservative approach indicates that even a single waveform can excite CNS or PNS.

<u>The Uncertainty of the Spectrum Analyzer:</u>

The uncertainty for the total ER was calculated based on UKAS 2000 [33] methodology, using type A and type B factors. In type B, factors such as linearity, anisotropy, flatness, frequency response, temperature, relative humidity with the contribution of calibration uncertainty, and ageing have been considered. In the following Table 2.1 we present the uncertainty budget considered in our calculations.

Table 2.1. Type B uncertainty budget used in University of Thessaly ELF measurements.

Type B Uncertainty						
Uncertainty Factor X_i	**Uncertainty x_i, dB)**	**Distribution**	**Divisor, k**	**Typical Uncertainty u(xi)**	**Weighting, c_i**	$(c_i\ u_{(xi)})^2$
Anisotropy	0,120	Rectangular	1,73	0,07	1	*0,005*
Frequency Calibration (Frequency response)	0,460	Rectangular	1,73	0,27	1	*0,071*
Flatness (40Hz-100KHz)	0,350	Rectangular	1,73	0,20	1	*0,041*
Linearity	0,180	Rectangular	1,73	0,10	1	*0,011*
NBM meter instrumentation	0,010	Rectangular	1,73	0,01	1	*0,000*
NBM meter noise and offset +/- 0.01uW/cm²	0,090	Rectangular	1,73	0,05	1	*0,003*
Extended Level Meas. Uncertainty (amplitude)	0,300	Rectangular	1,73	0,17	1	*0,030*
Humidity uncertainty (between 10-50C or out of range)	0,350	Rectangular	1,73	0,20	1	*0,041*
Temperature uncertainty (between 10-50C or out of	0,184	Rectangular	1,73	0,11	1	*0,011*
Body Influence (@2m)	0,000	Rectangular	1,73	0,00	1	*0,000*
Ageing	0,000	Rectangular	1,73	0,00	1	*0,000*
Συνδυασμένη Τυπική Αβεβαιότητα ΤΥΠΟΥ Β	$u_c(y) = \sqrt{\sum_{i=1}^{n}(c_i * u_{(x_i)})^2}$					**0,46**
Συνδυασμένη Τυπική Αβεβαιότητα ΤΥΠΟΥ Α	0,430	Κανονική	1	0,430	1	0,185

The uncertainty estimation for NBM 550 combined with EHP-50F antenna yields that the expanded uncertainty of the measured magnetic flux B is 15.62% with a confidence interval around 95% (k=2). The sources of the budget were the calibration sheets (issued by NARDA company), the official manuals of the EHP 50F device and probe, and international standards.

The Protocol of the Study

The objective of this study is to provide quantitative ELF exposure assessment at areas of sensitive land use such as schools and kindergartens. An initial survey was performed at the perimeter of the school buildings, to detect the highest field strength spot. As the electrical wiring is commonly insulated or even hidden, it was only the MF (magnetic field) that was usually measured, and the EF (electric field) was measured close to high voltage power lines. The reason is that in general the EF sustains strong shielding. MFs penetrate the body almost unperturbed (the body's magnetic permeability μ is approximately the same as that of the vacuum μ_0), generating induced currents perpendicular to the field. On the other hand, the EF sustains a strong shield entering the body, creating much smaller induced currents in the direction of the field. The WPM calculates the exposure of the MF or the EF as the percentage of the maximum permissible exposure (100% of the limit) according to ICNIRP 1998 guideline (EI). Three (3) areas of measurements were selected in this study: a) urban, b) suburban, and c) power distribution parks (high voltage). The study also targeted to conclude on the differences between these three environments. We selected 247 outdoor points of measurement with the following distribution: a) 196 measurements refer to urban environment, b) 39 to suburban, and c) 12 points are close to power distribution parks (high voltage). "Power distribution parks" spots represent locations close to power distribution stations at a distance between 300 to 1300 m from the park's entrance. The responsible engineers are located as much closer as possible to the parks in general public accessible areas. The main ELF source, for all the measurements, is the 50 Hz power frequency (dominant frequency), but other harmonics (k*50 Hz) were also detected. A characteristic case is presented in the Fig. 2.1:

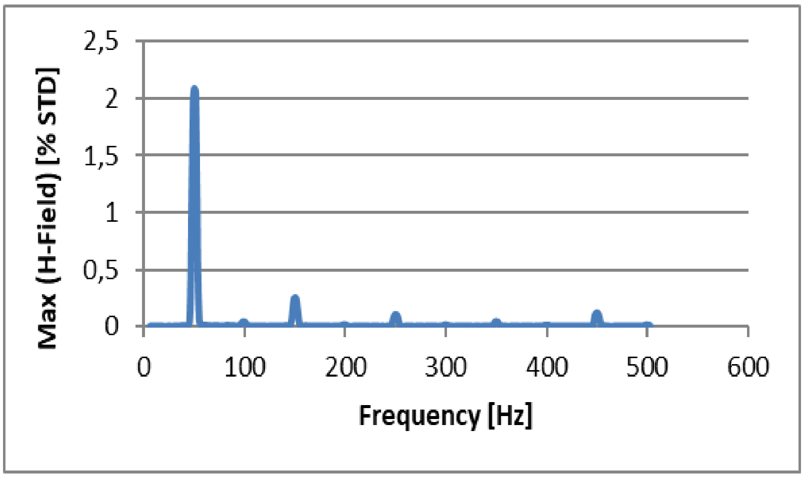

Figure 2.1. A typical spectrum of 50 Hz power supply. Other harmonics 150,250,350, and 450 Hz are also detected.

2.1.3 Results

Two types of results are presented:

(a) **Magnetic field flux B (μT)** measured in the "HIGHEST PEAK MODE" (50 Hz) keeping the "MAX HOLD" value following 4 full-span scans in the frequency range from 6 to 500 Hz and (b) the weighted percentage value of the ICNIRP 1998 safety limit using the **Weighted Peak Method (WPM)** mode. The WPM value covers the entire available range from 1 to 400 kHz (Wideband mode, MAX value kept following 4 full-span scans).

Mean values recorded are 0.21 μT for urban, 0.14 μT for suburban, and 0.49 μT for power stations. The maximum values recorded are 2.09 μT for urban, 0.53 μT for suburban and 1.90 μT for power stations. Taking into consideration the worst-case scenario where the uncertainty value is added we concluded that the maximum values are 2.41 μT for urban, 0.61 μT for suburban and 2.20 μT for power stations (Fig.2.2). Median values: 0.18 μT for urban, 0.11 μT for suburban, and 0.01 μT for power parks, have been analyzed based on Mood's Median Test (95% confidence interval). The result of the comparison test did not support any significant statistical difference between the three (3) environments (P value = 0.13 > 0.05). It is worth noticing that the 75% of values are below 0.25 μT for urban, 0.18 μT for suburban, and 0.85 μT for locations near power parks (Fig. 2.3). Mean WPM Exposure Index (EI) values recorded are 1.31% for urban, 1.20% for suburban, and 1.57% for power stations. The maximum percentage is 2.79 % for urban, 1.59 % for suburban, and 2.70 % for power stations (Fig. 2.4). In the worst case, with the expanded uncertainty added to the max value of the field strength, the result is still well below the safety limit (worst scenario: 3.23 % of the safety limit for urban, 1.84% for suburban, and 3.12 % for power stations). A Mood's Median test (95 % confidence level) used to determine if there were differences in median values of magnetic flux density B (μT) between urban, suburban, and close to power stations environments. Median values for urban (0.181 μT), for suburban (0.110 μT), and for power stations (0.095 μT), concluded that there is not statistically significantly difference. ($P = 0.126 > 0.05$). It is illustrated in "boxes plots", that the value ranges between the three environment types are almost the same, resulting in no significant difference between the two types, verified by the Mood's Median test. Mood's median test is used to compare the medians for two samples to find out if they are different. This test is the nonparametric. Nonparametric means that there is no need to know what distribution the sample follows (i.e., a normal distribution) before running the test.

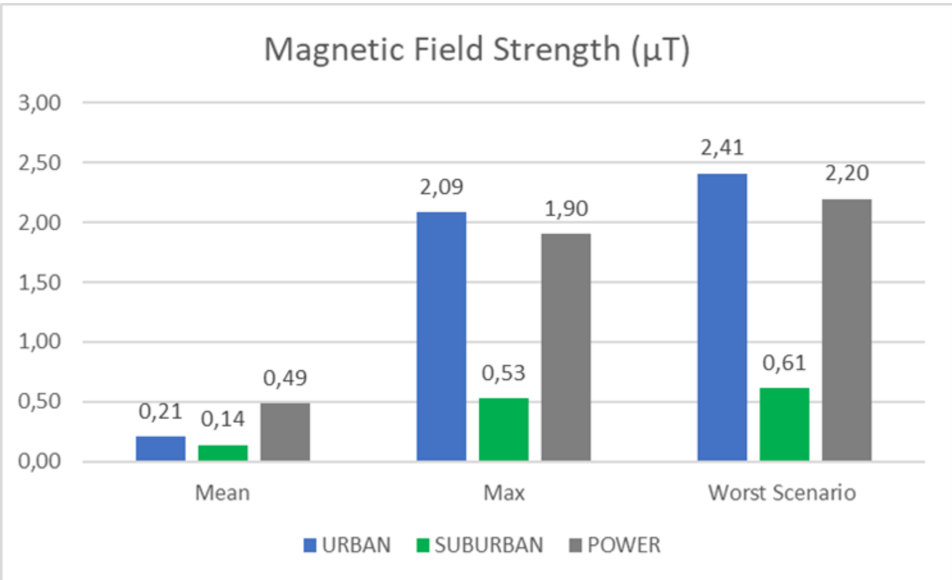

Figure 2.2. Min and Max values of the MF (Max Peak Mode) for urban, suburban, and power environments. Worst case scenario considers the uncertainty.

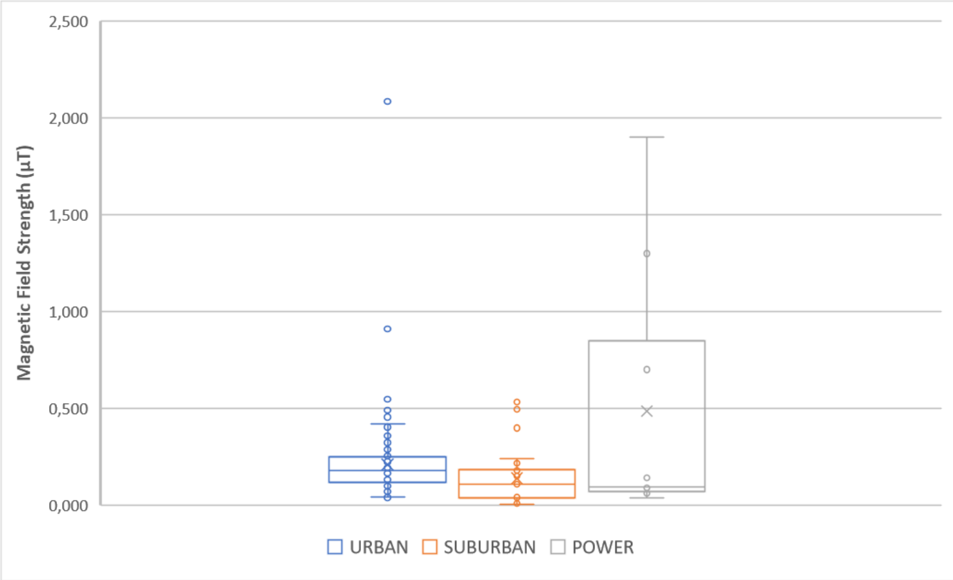

Figure 2.3. Comparison of the 3 environments - Max Hold Magnetic Field Flux (μT)

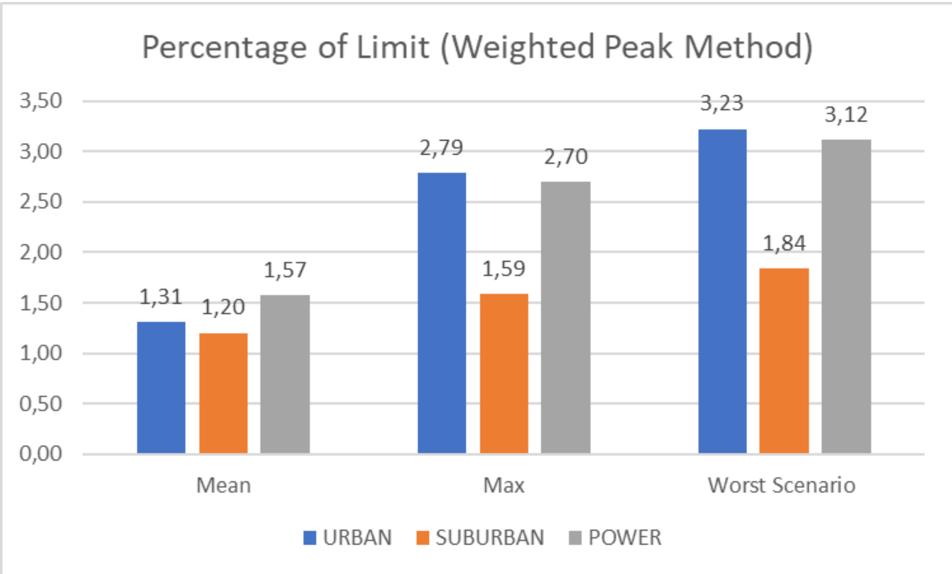

Figure 2.4. WPM - EI: Mean, maximum and the worst-case percentage of the limits for urban, suburban, and power environments.

According to the Greek Atomic Energy Commission (2006) measurement database, the following table presents typical values (outdoor) of magnetic and electric field in the vicinity of Power distribution lines of different voltage. All field strength values refer to 1.5m height from the ground (Table 2.2).

Table 2.2. Outdoor magnetic and electric field derived from power lines in Greece at 1.5m height from the ground.

Source	**Spot**	**Magnetic field (μT)**	**Electric field (V/m)**
400 kV distr. lines	Max value (under the power lines)	25	5000
	Typical value (under the power lines)	1-4	2000-4000
	Typical value (25m on the side)	0.5-2	200-500
150 kV distr. lines (metallic pillar)	Max value (under the power lines)	15	2000
	Typical value (under the power lines)	0.5-2	1000-2000
	Typical value (25m on the side)	0.1-0.2	100-300
150 kV distr. lines (metallic mast)	Max value (under the power lines)	10	1200
	Typical value (under the power lines)	0.3-1.5	500-1000
	Typical value (25m on the side)	0.05-0.2	50-100

20 kV distr. lines	Max value (under the power lines)	5	700
	Typical value (under the power lines)	0.2-0.5	200
	Typical value (25m on the side)	0.01-0.05	10-20

2.1.4 Discussion

ELF measurements at the vicinity of sensitive land use (schools) were performed. The results were compared against the limit of 100 μT (ICNIRP 1998), which is the approach followed by the Greek government. EU and ICNIRP have adopted since 2010 an increased limit of 200 μT (ICNIRP 2010). Max Peak mode and the WPM have been followed for conservative purposes to assess human exposure with a considerable safety margin. Discussing the differences between the 3 different environments of this study, higher values were recorded at the high voltage (power parks) locations, and for the urban relative to the suburban locations. However, the highest value has been recorded to an urban location, probably because of high voltage underground networks. Statistical analysis (Moods Median Test) indicated that there is no statistically significant difference between the 3 environments. In this sense the slightly increased values near high voltage installations (in the sense of Max Peak measurements) are of no importance. Future work could incorporate personal exposimeters, to improve exposure assessment. According to Gallastegi et al., 2018 publication [34], spot measurements overestimate RF exposure levels compared to personal dosimeters' data. Personal exposimeters are worn almost 24hrs highlighting the real human exposure which is relevant to the individual way of life. The exposure from ELF near power lines (distribution parks) is quite low compared with the strictest 2010 limit.

Other studies on ELF public exposure are in accordance with our investigation. In Christopoulou's 2019 study [35], the median values for urban and suburban environment were 0.144 μT and 0.140 μT respectively. The max value in urban areas was 2.24 μT (2.09 μT in our study), and 4.84 μT in suburban (0.53 μT in our study). An interesting study took place in Serbia by Vulevic et al., 2011 [36] in 35 municipalities. ELF households' exposure from overhead power lines was assessed. Power lines of 400 kV, 220 kV, and 110 kV were included in 100 measurement points. The max magnetic field recorded was 4 μT, 2.5 μT, and 2 μT respectively at distances below 30 m from the nearest phase of the power line. Moreover, measurements under the power line were performed. For the 400 kV installation at 15m height, the max magnetic field was 3.2 μT, whereas for the 220 kV the B_{max} was 3 μT. All measurements were kept well below the ICNIRP's 2010 and 1998 limits. In our study, the max magnetic field strength was 1,90 μT (2.20 μT if the uncertainty is added to the result). The results are in accordance. Based on [37], the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) declares that: "at ground level, directly below powerlines, magnetic fields reach as much as 20 μT and electric fields can be between several hundred and several thousand of volts per meter (~100 V/m - ~10 kV/m)". Following an important review [38] on Low EMF exposure in Europe by Gajsek et al., 2016 [38]: "400 kV underground cables can produce a magnetic field intensity of over 30 μT at ground level, falling to 10 μT at 2 m above the ground, since the field intensity falls very rapidly with increasing distance from either side." Moreover, a 400 kV electricity pylon can produce a magnetic field of around 10–20 μT directly under the installation, whereas the produced electric field ranges from 3 to 5 kV/m. These levels fall with distance (inverse square law) from the sides of the line. Typical UK values at the perimeter fence of power stations, were 10 μT for 275 and 400 kV substations, and 1.6 μT for an 11 kV substation. In the same study, ELF magnetic fields strength measurements concerning urban only areas took place in Spain, Italy, Sweden, and Norway. The average MF was 0.2 μT in

Spain, a median of 0.2 μT recorded in Sweden, in Italy a median of 0.08 μT with a mean of 0.19 μT, and in Norway an average of 0.13 μT (in summer) and 0.85 μT (in winter).

As a conclusion, the outdoor average exposure in urban locations ranges from 0.05 to 0.2 μT, whereas higher field values are met beneath high-voltage power lines, on the walls of transformer buildings, and at the boundary fences of power substations where the magnetic field that can be recorded ranges from 20 to 80 μT.

2.2 Indoor Exposure (Households)

2.2.1 Introduction

The widespread use of electricity means that people are exposed to ELF electric and magnetic fields in the home, in the environment and in the workplace. Residential exposure to ELF fields depends on many factors, including the distance from local powerlines, the number and type of electrical appliances in use in the home, and the configuration and position of household electrical wiring.

2.2.2 Household Typical ELF Exposures

The German Study

In the following Table 2.3, typical values of magnetic fields produced by household appliances are presented by the German Commission on Radiological Protection in 1997 (report issue 7). The MF decreases with the distance. Electrical appliances are not used very close to the body, and this is a protective measure for people. The adopted safety limit for the MF strength according to ICNIRP 2010 guidelines, is 200 μT at 50 Hz for the general public (in Greece, ICNIRP 1998 is still in use, thus the limit is 100 μT at 50 Hz).

Table 2.3. Typical fields in residential environment from German Commission on Radiological Protection (1997).

Electric appliance	Magnetic field density (μT) at 3	Magnetic field density (μT) at 30	Magnetic field density (μT) at 1 m
Hair dryer	6-2000	0.01-7	0.01-3
Electric razor	15-1500	0.08-9	0.01-3
Electric drill	400-800	2-3.5	0.08-0.2
Vacuum cleaner	200-800	2-20	0.13-2
Fluorescent lamp	40-400	0.5-2	0.02-0.25
Microwave oven	73-200	4-8	0.25-6
Portable radio set	16-56	1	< 0.01
Electric cooker	1-50	0.15-0.5	0.01-0.04
Washing machine	0.8-50	0.15-3	0.01-0.15
Iron	8-30	0.12-0.3	0.01-0.03
Dishwasher	3.5-20	0.6-3	0.07-3
Computer	0.5-30	< 0.01	< 0.01
Refrigerator	0.4-1.7	0.01-0.25	< 0.01
Television set	2.5-50	0.04-2	0.01-0.15

The Australian Study

According to ARPANSA [37], the background magnetic fields in the home are usually around 0.1 μT. Background electric fields in the home can be up to 20 V/m. Near some appliances, the instantaneous magnetic field values can be as much as a few hundred micro-Tesla and the electric field several hundred volts per meter.

The Greek Study

Greek Atomic Energy Commission (GAEC) issued in 2007 a factsheet with ELF exposure information. In the following Table 2.4, we may find magnetic field strength range at specific distances from electrical appliances used in home environment.

Table 2.4. Residential ELF exposure from electrical appliances based on international bibliography (issued 2007, Greek Atomic Energy Commission)

Electrical	At 3 cm distance (μT)	At 30 cm distance (μT)	At 1 m distance (μT)
Electric Shaver	10-900	0.05-9	0.01-0.2
Hair Dryer	8-800	0.07-7	0.01-0.03
Fluorescent	40-400	0.5-2	0.02-0.25
Electric oven	1-50	0.15-0.5	0.01-0.04
Microwave	5-100	0.4-8	0.15-0.5
Refrigerator	0.5-1.7	0.01-0.3	0.01-0.05
Washing	0.8-40	0.15-3	0.01-0.15
Washing	1-15	0.2-2	0.07-3
Iron	3-30	0.14-0.3	0.01-0.03
Vacuum cleaner	60-500	0.8-12	0.08-0.8
Portable radio	1-15	0.4-1.5	0.01-0.1
TV	2-80	0.04-8	0.01-0.9
Video camera	0.6-20	0.7-2.5	0.01-0.03
Photocopier	0.6-40	0.1-2.7	0.01-0.3
FAX	0.4-1.5	0.01-0.2	0.01-0.02
PC monitor	1-60	0.02-5	0.01-0.6
Electric drill	4-200	0.2-3.3	0.01-0.8

2.2.3 University of Thessaly (Medical Physics Lab) Indoor Investigation

Indoor electrical appliances considerably contribute to human exposure for 24hrs. During this Ph.D. work, we performed measurement inside a house located in urban area, not close to power lines (above 500 m distance from power lines). In the following Table 2.5, the exposure levels close (in percentage values of the ICNIRP 1998 limit) to electrical appliances (at 50 Hz) are presented.

Table 2.5. Percentage of electric (E) and magnetic (H) ICNIRP 1998 limit field inside a house (max E and H values are considered).

Location	H% max	E% max
Balcon (outdoor)	0,50	12,30
PC transformer OFF - multiple sockets at 20 cm	0,51	6,26
PC transformer ON - multiple sockets at 20 cm	10,42	19,80
TV front (transformer ON)	0,48	8,30
TV back (transformer ON)	0,46	7,70
Kitchen area (in the middle)	0,40	5,50
Kitchen area (in the middle) with multiple sockets	3,12	20,97
Electric oven front (ON)	0,62	17,13
Refrigerator (front)	0,45	6,12
Bedroom (sleeping) devices OFF	0,35	5,50
Bedroom (sleeping) devices ON	0,41	5,70
Livingroom in the middle with lights and TV ON	0,46	5,60
Livingroom in the middle with lights and TV OFF	0,38	1,60
Table light - Lamp LED at 1-2 cm	0,40	152,20
Table light - Lamp LED at 20 cm	0,42	60,36

Elevator moving (inside cabin)	2,50	N/A
Elevator stopped (inside cabin)	0,37	N/A

2.2.4 Discussion

In Germany, 1835 residences were assessed by Schüz et al., 2000 [39], for exposures at 50 and 16.7 Hz in children's bedrooms for 24 hrs. In 1.4% of residences, median values of above 0.2 μT were recorded at 50 Hz. Higher magnetic fields of 0.3 μT were met in 0.4% of cases, and 0.4 μT in 0.2% of residences. The median exposure derived from high-voltage power lines (123–420 kV) was higher than 0.2 μT for only 32.0% of cases that were located 50 m or closer to a power line. In the UK, a week-long survey of power-frequency magnetic field measurements was conducted in 258 homes [40]. The presence or absence of overhead power lines at voltages of above 132 kV within 100 m from the home was the critical factor of influencing or not the indoor exposure. The geometric-mean of time-weighted average fields measured was of about 0.2 μT within 100 m from the lines, and 0.054 μT at distances greater than 100 m. According to Maslanyi, 2016 [41], 196 homes were assessed and categorized into high (> 0.2 μT) and low (< 0.2 μT) exposure level. For 102 homes the exposure was above 0.2 μT. Based on Khan et al., 2010 thesis [42], ELF field measurements were performed in 100 houses in Sweden, located at urban areas or in countryside. Approximately 90% of the houses presented MF strength below 0.2 μT, with a mean value of 0.11 μT and a median value of 0.05 μT. The magnetic field was higher on the ground-floor areas as compared to other floors. Underground heating systems and the electric wiring in the houses were the reason of this deference. Finally, WHO collected data from various countries [40] with no considerable differences: In Finland, the geometric mean is 0.060 μT, in Germany between 0.026 and 0.029 μT, in Sweden between 0.037 and 0.048 μT, and 0.029 to 0.064 μT in the UK. According to Preece et al., 1997 [43], 50 houses were assessed in the UK. Magnetic fields at various distances from domestic appliances were measured. Fifty (50) Hz fundamental and harmonic waves were generated. Few appliances generated fields higher than 0.2 μT at 1 m: microwave cookers field was 0.37 μT; washing machines 0.27 μT; dishwashers 0.23 μT; specific electric showers 0.11 μT; and can openers generated fields of 0.2 μT. Concerning devices that operate continuously, 3 devices generated fields of some tens of μT at 0.5 m: central heating pumps' field of 0.51 μT, central heating boilers 0.27 μT, and fish-tank air pumps 0.32 μT. It is worth noticing that most of daytime is spent in the kitchen, where the strongest magnetic fields sources are found. According to Bedja et al., 2010 [44], the French government initiated a large study of personal exposure of the French population to 50 Hz magnetic fields. A thousand (1000) of children from 0 to 14 years old and 1000 adults formed the database. Personal exposure measurements were collected from 2007 to 2009. The mean value calculated was 0.09 μT for children and 0.14 μT for adults. Concerning the awake period, mean exposures were 0.05 μT for children and 0.10 μT for adults. The percentage of children with a 24 hrs. mean exposure higher than 0.4 μT was 3.1 %. Highest exposures were recorded when the dosimeter was found close to an electric appliance with a transformer. The mean 50 Hz magnetic field exposures were stronger for adults than for children. The children were more exposed inside the home than outside, while the opposite was for adults. At home, both adults and children were more exposed during the day than during the night. In Germany, 1952 people participated in a study Brix et al., 2001 [45], targeting to measure magnetic field exposure at 50 Hz and 16.7 Hz between 1996 and 1997. The average of the individual flux density was 0.1 μT and the median was 0.047 μT at 50 Hz. Only 2.4 % of the measurements were higher than 0.2 μT. Regarding the exposure from railway the mean value recorded at 16.7 Hz was 0.156 μT, and the median was 0.102 μT. UK Childhood Cancer Study Investigators' study [46] on 1999 provided no evidence that exposure to magnetic fields associated with the electricity supply in the UK increases risks for childhood leukemia, cancers of the central nervous system, or any other childhood cancer

Exposure to Intermediate Frequencies (IF) - between 300 Hz and 10 MHz

Few studies are referred to the general public exposure to F fields derived from electronic article surveillance, energy saving bulbs, induction cookers. Electronic article surveillance (EAS) systems are used to prevent theft in shopping areas. According to Joseph et al., 2012 [47] study: "*exposure of EAS systems was investigated in situ for both the detection gate panels and the activators and deactivators. For the detection gates, the spatially averaged fields exceeded the reference levels for five of the six investigated systems"*. In the first decade of 2000, incandescent light bulbs were replaced in the EU and other areas. Compact fluorescent lamps selected to be used instead exhibit IF radiation (Intermediate Frequency electric fields) much stronger than any other device or appliance. Energy saving lamps are emitting at 30–60 kHz. ELF exposure is also present following Dürrenberger et al., 2004 [48]. Electric field maximum strength (in the 1.2–100 kHz frequency range) close to the lamps was almost 42 V/m in most lamp cases. In the 50% of measurements, the field strength exceeded 87 V/m, and the highest recorded value was 216 V/m. ICNIRP guidelines are followed but the large variations among the bulbs cannot ensure that these energy saving solutions are 100% compliant with the ICNIRP safety limits.

2.3 Conclusion

The conclusion, based on the current state of knowledge, is that the average exposure of the general public in European countries is too low, up to 0.1 μT. Approximately 0.5% of the population is exposed to levels above 0.2 μT derived from the power distribution installations (i.e., high-voltage power lines, lines of transport systems). Household electric devices consist of a major source of public exposure, but the duration of such exposure is extremely limited in most cases. High levels of magnetic fields are reported in the kitchen or close to transformers. In terms of cumulative exposure, approximately one third of the total exposure experienced by an individual can be attributed to the use of personal appliances. ELF levels in the European population are significantly below the ICNIRP's limits at 50 Hz, both for 2010 guidelines (200 μT) and 1998 guidelines (100 μT). Moreover, technological changes in Europe during the last years have led to the introduction of new LF sources. For example, LED lamps are being used instead of energy-saving lamps, electric cars, and batteries from mobile phones, tablets, laptops.

Chapter 3: Radiofrequency (RF) Exposure in Greece

3.1 Introduction

Radiofrequency (RF) Spectrum ranges from 100 kHz to 300 GHz. Human exposure comes from various sources depending on the evolution of technology and modern style of life. Wireless technology is being used daily, with mobile communications at the top of people's concerns about their health impact. GSMA Intelligence's numbers indicate that mobile connections in Greece were equivalent to 144.3 percent of the total population in January 2022. Based on the "Datareportal" study for Greece in 2023 (https://datareportal.com/reports/digital-2023-greece), 80.5 % of Greece's population lived in urban centers, while 19.5 % lived in rural areas. Internet penetration rate reaches 84 % of the total population with a median mobile internet connection speed via a cellular network of 61.4 Mbps. According to the Ministry of Digital Government, 17000 mobile base stations are installed in Greek territory, while more than half are in Athens. Three operators provide mobile and fixed services: Cosmote, Vodafone, and Nova. Spectrum allocated for mobile ranges from 700 MHz to 3500 GHz. Second-generation technology (2G) uses the 900 MHz band, 3G uses 900 and 2100 MHz, 4G uses 1800 and 2600 MHz, and 5G is emitted at 700, 2100, and 3500 MHz. Other RF-licensed services are Meteorological, Military (used in national defense), Aeronautical and Marine, Radio and TV broadcasting, Mobile Base Stations (BS), Digital Enhanced Cordless Telecommunications (DECT/wireless phones), RF Identification tagging systems (RFID), Wi-Fi, WLANs, Instrument Landing Systems (ILS), TETRA, and Space Research Technologies systems.

Note: At the time of the project, the 3 operators in Greece could not use the band of 700 MHz. So, the narrowband results did not include this service. Moreover, the electric probe used (as described below) had the capability to detect frequencies in the range 27 MHz to 3000 MHz. Thus, C-band (3500 MHz 5G) exposure was not included. 5G roll out was very limited (in pilot mode in 3 cities only).

3.2 The Scope of Study

This Ph.D. work had the scope to measure (and then evaluate) the RF radiation levels in areas of sensitive land use in Greece (Alexias et al., 2020 [49]; Tyrakis et al., 2020 [50]; Kiouvrekis et al., 2020 [51]; Tyrakis et al., 2023 [52]). The objective is to evaluate the current RF exposure levels in Greece, before the massive rollout of 5G technology, in areas of sensitive land use (schools, universities, kindergartens, elderly homes, hospitals, and playgrounds). Measurements were part of the National EMF research program (EDBM34) with the participation of the University of Thessaly (School of Medicine).

3.3 Method and Material

The Spectrum Analyzer

SRM 3006, manufactured by NARDA Safety Test Solutions, (Pfullingen, Germany) was used by our laboratory to perform electric field strength measurements. The device consists of the main unit and the detection probe.

Main Unit:

The detection range of the main unit ranges from 9 kHz to 6 GHz. Measurement ranges from -30 dB to +20 dB in steps of 1 dB. It provides two operation modes a) Spectrum Analysis and b) Safety Evaluation. The "Safety Evaluation" mode is preferred when the scope is to evaluate compliance with pre-selected safety limits.

Detection Antenna (probe):

The detection probe is an isotropic 3-axis antenna recording the electric field strength (E). The frequency of the antenna type used (3501/03) ranges from 27 MHz to 3 GHz. The typical dynamic range is from 0.2 mV/m to 200 V/m while the destruction limit is at 435 V/m.

Safety Evaluation Mode Used in measurements:

SRM 3006 provides a mode suitable to assess every selected frequency band for compliance with (pre-selected) safety limits. Our assessment was based on the ICNIRP's 1998 [5] and 2020 [3] frequency limits. It is worth mentioning that Greek legislation (Law 4635/2019) adopt an additional safety factor, introducing stricter values for the general public EMF exposure than ICNIRP's guidelines and EU's Council Recommendation [53] (1999). Greek legislation introduces a 30% and a specific 40% decrease in cases of sensitive land use (schools, kindergartens, elderly homes, and hospitals) in a 300 m perimeter from the examined RF antenna.

<u>Operational Settings:</u>

Operating Mode: Safety Evaluation

Frequency Range: 27 MHz – 3 GHz

Unit of measurement: V/m (electric field strength)

Results type: Average

Time average: 6 min

RBW setting: 1 MHz.

Measurement Range (MR): 5 V/m (no overdriven detected)

Sweep time setting: Automatically (around 6 sec)

Video bandwidth setting: Off (automatically selected)

Noise Cap setting: Off

<u>The Uncertainty of the Spectrum Analyzer:</u>

The uncertainty [33] was calculated for the total ER using type A and type B uncertainty budget. In type B, factors such as anisotropy, level measurement accuracy, frequency response, linearity, mismatches, calibration uncertainty, cable loss calibration uncertainty, temperature response, and ageing have been considered. In the following Table 3.1 we present the uncertainty budget considered in our calculations. The sources of the budget were: the calibration sheets (issued by NARDA company in 2018), the official manuals of the SRM 3006 device and probe, and the international standards. It is worth mentioning that spectrum analyzers used in such very dynamic measurements (as the electric field strength from RF sources) exhibit large uncertainty margins, many times above 50 %. This is a typical value for most laboratories in the world using SRM 3000 or SRM 3006.

Table 3.1. Type B uncertainty budget for the SRM 3006 device with the antenna probe 27-3000MHz.

Typical Uncertainty Type B							
Uncertainty Factor X_i	Uncertainty x_i, (%)	Distribution	Divisor k	Typical Uncertainty u(xi)	Weighting Factor c_i	$(c_i \, u_{(xi)})^2$	Reference
Isotropy Measurement	12,070%	Rectangular	1,73	0,07	1	*0,005*	*Calibration 2018*
Frequency Calibration (Frequency response)	0,000%	Rectangular	1,73	0,00	1	*0,000*	*Calibration 2018 - the unit didn't calibrated standalone*
Frequency Calibration Interpolation (Frequency Response - Antenna)	0,330%	Rectangular	1,73	0,00	1	*0,000*	*ELOT 1422-3 (FIRST ISSUE)*
Frequency Calibration (Frequency response - Cable)	30,000%	Rectangular	1,73	0,17	1	*0,030*	*Calibration 2018*
Extended Level Meas. Uncertainty (amplitude)	12,000%	Rectangular	1,73	0,07	1	*0,005*	*Calibration 2018*
Temperature uncertainty (between 10-50C or out of range)	13,500%	Rectangular	1,73	0,08	1	*0,006*	*Narda product data sheet 28th of June 2006; (1,1 or 2,2 db)-*
Body Influence (@2m)	18,850%	Rectangular	1,73	0,11	1	*0,012*	*ELOT EN 50492 (2008)*
Ageing	0,000%	Rectangular	1,73	0,00	1	*0,000*	*manual*
Combined Uncertainty Type B	$u_c(y) = \sqrt{\sum_{i=1}^{n} (c_i * u_{(x_i)})^2}$				24,02%		

Exposure Ratio (ER) uncertainty follows the method described in the Greek standard ELOT/EN 1422-3 [54] and the international (ETSI TR, 2001a [55]; ETSI TR, 2001b [56]) standards. The expanded uncertainty was calculated at 3.66 dB (Type A and Type B) for 95% confidence interval (k=1.96). According to our calculations, RF measurements exhibited an uncertainty value of 52.41%.

The Protocol of the Study

Two types of measurements can be performed while assessing EMFs. (a) Spot measurements using broadband or narrowband selective meter (spectrum analyzer) and (b) personal exposimetry (personal monitoring). In this study, RF exposure levels were assessed by applying spot measurements. Considering the frequency selective measurements, fifty-four (54) bands (according to the Greek spectrum allocation) are included in the 27 to 3000 MHz measurement range. For each of the 54 bands (for i=1 to 54), the electric field strength (Ei) is measured as the average value in 6 min period. ICNIRP's 1998 and 2020 guidelines define the Reference Levels for the incident electric field strength (V/m). The reference levels are frequency dependent. For simultaneous exposure to multiple frequency fields (ICNIRP, 1998) [5], the total Exposure ratio (ER) is calculated as the sum of all the squared ratios of the electric field strength for the band i (Ei) to the limit of this band i (ELi). To be conservative in our evaluation, we use the limit corresponding to the lowest frequency of each band i (this is the strictest limit for each band). For example, the lowest frequency for the FM Radio band is 87.5 MHz. The total ER limit is the unit.

Areas of measurements: Seven (7) out of 13 regions in Greece were covered (Fig. 3.1). East, Central, and West Macedonia, Attica, Peloponnese, Thessaly, and Crete. As a result, 78.89% of the total Greek population was covered. The areas of measurements were divided into two big classes. The concept was to distinguish dense networks usually installed in big towns from sparse networks usually met in rest urban areas. Based on this, we consider: (a) Metropolitan areas, involving Athens and Thessaloniki as the two most crowded towns with the majority of mobile installations, and (b) Rest Urban / Rural areas covering the rest of Greece. A thousand (1000) points of interest were selected (624 in metropolitan areas and 376 in the rest of Greece). We must clarify that no rural areas were selected (for example top of mountains, top of hills, outside the main urban fabric). As mentioned, the scope of the project was to evaluate the exposure in sensitive land use cases such as schools, hospitals, kindergartens, universities, elderly homes, playgrounds).

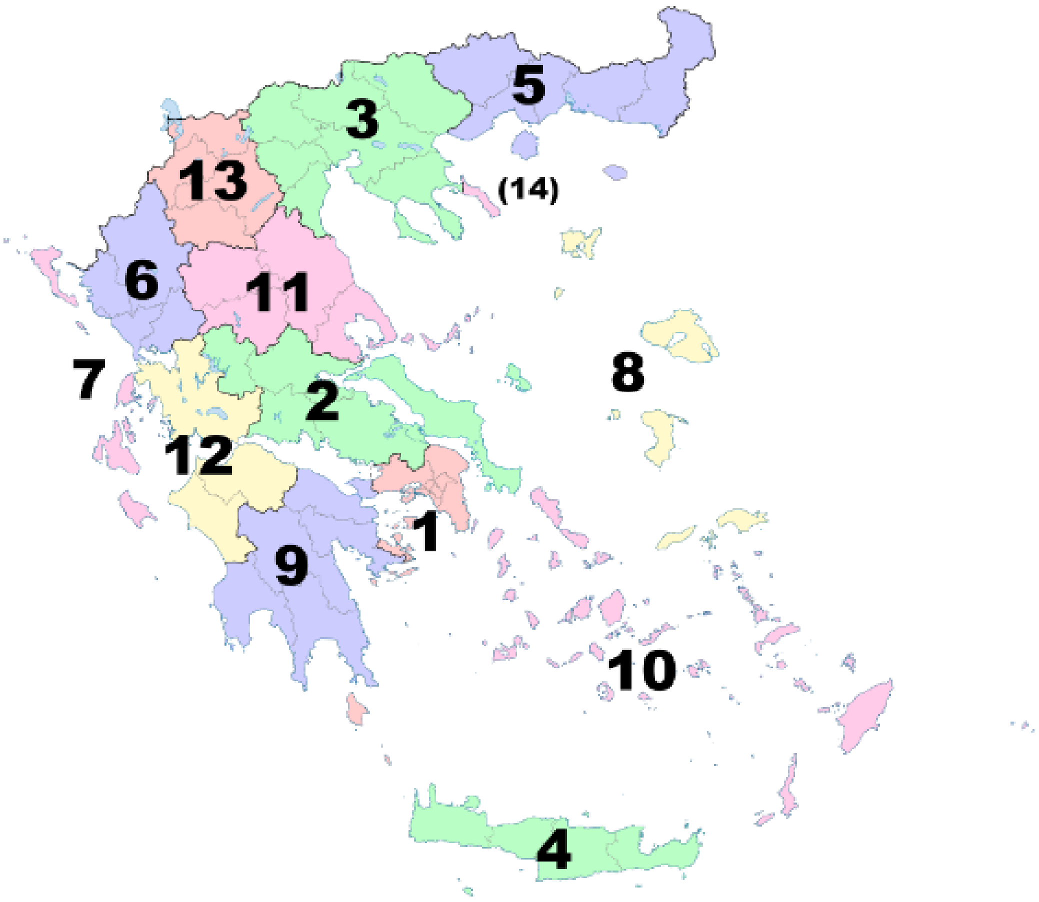

Figure 3.1. Regions of measurements: 1 (Attica), 3 (Central Macedonia), 4 (Crete), 5 (Eastern Macedonia and Thrace), 9 (Peloponnese), 11 (Thessaly), 13 (Western Macedonia).

The measurement protocol is described briefly:

(a) All measurement points were located outdoors, at the perimeter of schools, universities, kindergartens, elderly homes, hospitals, and playgrounds (sports centers): Seven hundred and thirteen (713) measurements (out of 1000) are associated with schools and universities, 245 (out of 1000) with kindergartens or elderly homes, 16 (out of 1000) with hospitals, and 26 (out of 1000) with playgrounds or sports centers.

(b) The "worst-case scenario" was selected. This means that an initial broadband survey was performed at each location, indicating the spot with the highest power density. According to the Greek Atomic Energy Commission (Decision No 2300 / 3-3-2008), analytical, narrow-band measurements were performed at this spot.

(c) Clear sky and normal weather conditions were met: 15-20 ℃ / 45-55% humidity. (d) Measurements were carried out keeping the “Average” value of the electric field strength using an averaging time interval of 6 min. Moreover, a spatial average of the three heights (1.1 m, 1.5 m, 1.7 m) proposed by the Electronic Communications Committee Recommendation (02)04 [57] is taken into consideration. During our measurements, the electric field strength was very weak. There were no significant differences between the three height values. Measurements were performed at high-traffic hours (mid-day) to acquire a conservative estimation of the electric field strength. The unit device and the antenna system were kept 1m away from reflecting objects and the human body to avoid interactions or overestimations (ITU-T, 2018) [58]. The measurement method was based on the Greek Governmental Decision No 2300 published in March 2008

3.4 Results

1) Broadband Results (frequency range: 27 MHz to 3000 MHz):

Broadband electric field strengths for Metropolitan and the rest of Greece areas are presented (Fig. 3.2).

Metropolitan areas (Athens and Thessaloniki): The mean electric field strength (broadband result) out of 624 measurements was 0.41 V/m ranging from 0.28 V/m (min value) to 1.87 V/m (max value) with a median value of 0.34 V/m and median absolute value (MAD) 0.04. It should be noted that 75% of all measurements are below 0.44 V/m (75-percentile).

Rest Urban-Rural areas: The mean electric field strength (broadband result) out of 376 measurements in the rest of Greece was 0.36 V/m ranging from 0.27 V/m (min value) to 1.92 V/m (max value) with a median value of 0.30 V/m and median absolute value (MAD) 0.01. It should be noted that 75% of all measurements are below 0.36 V/m (75-percentile). Six (6) values are determined in Box and Whisker plots for both cases: Min and Max (whisker), Q1 (25th percentile), Median, Average (indicated with "x"), and Q3 (75th percentile).

Greece (total): The median out of all the 1000 measurements was 0.32 V/m, with 75% of the results below 0.42 V/m (background levels).

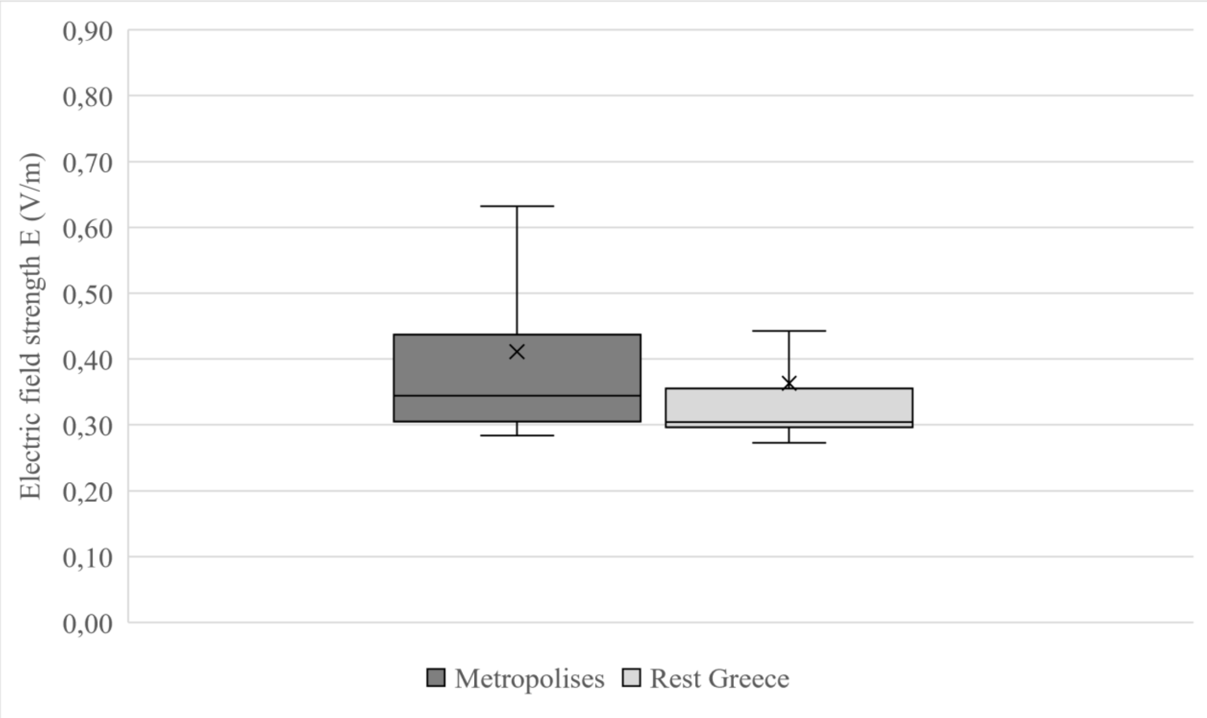

Figure 3.2. Box and Whisker plot of the broadband electric field strength (V/m) at Metropolitan areas and the rest of Greece. Min and Max (Whisker) and the interquartile range (Q1, median, average, and Q3) are illustrated.

2) Safety Guidelines compliance:

The total ER values for Metropolises and Rest Greece are illustrated in Box (interquartile range) and Whisker (minimum and maximum) plot. The limit of the total ER is unit (1). (Fig. 3.3)

Metropolitan areas (Athens and Thessaloniki): The median total ER was 0.078 x 10-3. The maximum recorded total ER was 1.293 x 10-3, or 0.129% of the ICNIRP's limit. Focusing on the mobile sector, downlink emissions exhibited a median ER of 0.004 x 10-3, with a maximum ER of 1.235 x 10-3 or 0.123% of the limit.

Rest Urban-Rural areas: The median total ER was 0.062 x 10-3. The maximum recorded total

ER was 1.097 x 10-3, or 0.110% of the ICNIRP's limit. Focusing on the mobile sector, downlink emissions exhibited a median of 0.003 x 10-3, with a maximum ER of 0.965 x 10-3 or 0.096% of the limit.

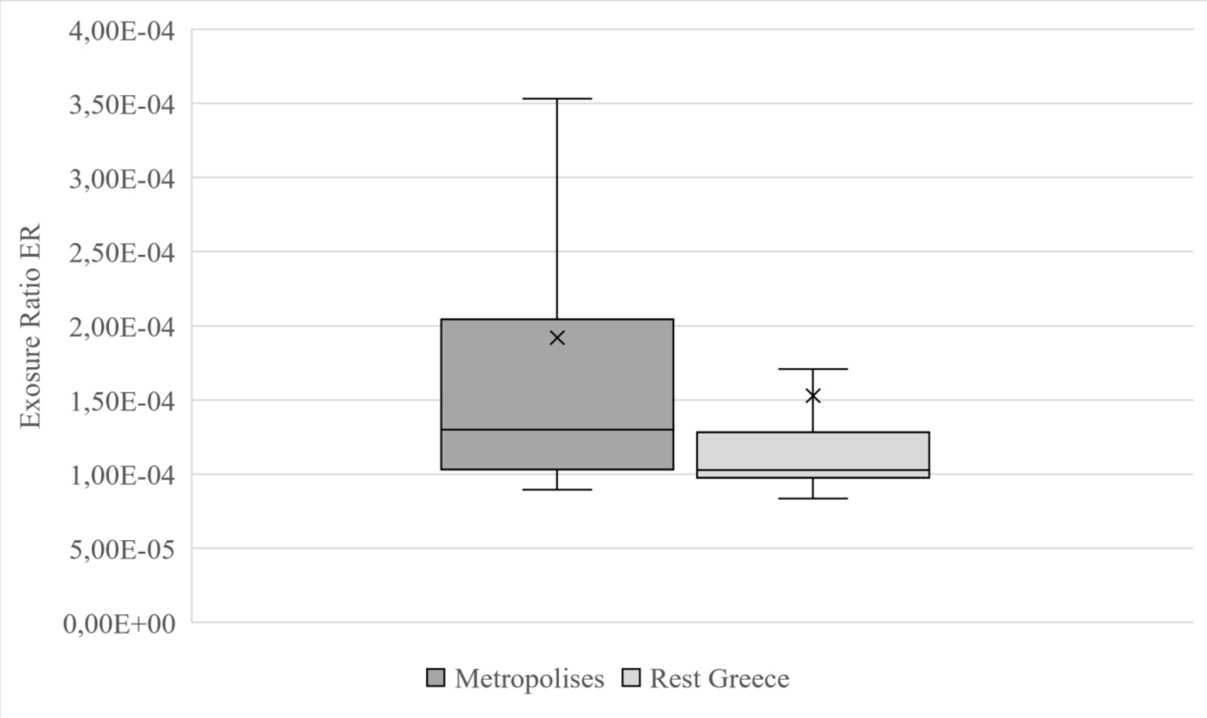

Figure 3.3. Box and Whisker plot of the total exposure ratio at Metropolitan areas and the rest of Greece. Min and Max (Whisker) and the interquartile range (Q1, median, average, and Q3) are illustrated.

3) Spectrum analysis:

It is of great interest to find out the predominant sources contributing to the total exposure in the two cases (Metropolitan and Rest Urban-Rural areas).

Metropolitan areas: The electric field strength (E) from 54 different services is measured. Based on these results (average value), we may conclude the contribution of each source to the total radio exposure. Radio FM and TV signals (87.5-108, 108-410, and 470-790 MHz) contributed 36.2% (average value) to the total ER (14.9% and 21.3%, respectively). Defense, Military, and Meteorological systems (27-87.5 MHz) contributed 24.9%. Mobile Communications (DL emissions) contributed 14.9% ranging from 0.6% to 95.5%, while 75%

of mobile RF cases were below 13.9%. Analyzing the mobile sector (the antennas are usually located at short distances to the residences), we found out that the 900 MHz signal was predominant with an average value of 4.5%. It is worth mentioning that Wi-Fi (2.4 GHz) signals were very low, with a 1.4% average contribution. (Fig. 3.4).

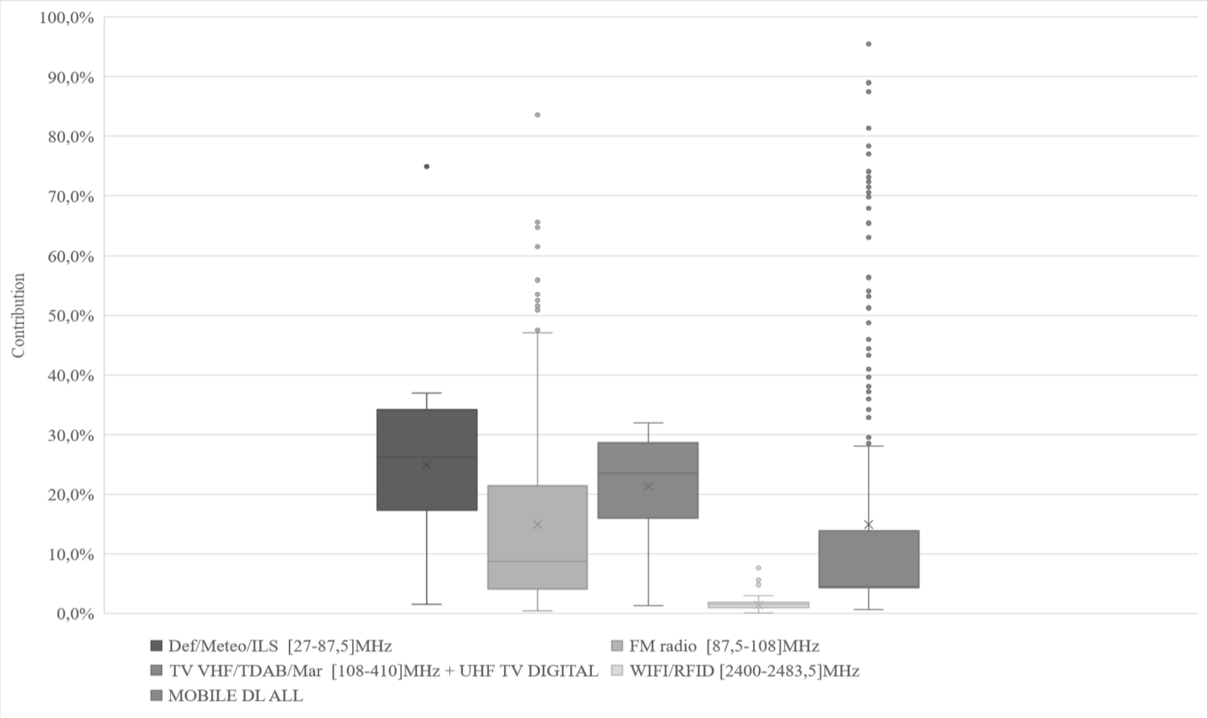

Figure 3.4. Box and Whisker plot of the contribution of RF sources in the total ER in Metropolitan areas. Min and Max (Whisker) and the interquartile range (Q1, median, average, and Q3) are illustrated. ER = exposure ratio; RF = radiofrequency.

Table 3.2 shows the average electric field strength in V/m for each band (54 bands are recognized in the Greek spectrum) and the broadband value for Athens and Thessaloniki (624 spots). Max values as well as the 25th, 75th, and 95th percentiles are presented. NARDA SRM 3006 spectrum analyzer's available probe detects frequencies from 27 MHz to 3000 MHz. At the time of the project 700 MHz band was not used by the 3 operators in Greece.

Table 3.2. Average electric field strength (V/m) per service band in Athens / Thessaloniki (values out of 624 points of measurement).

Service / Electric Field (V/m)	AVERAGE	MAX	25TH	75TH	95TH	SD
Def/Meteo/ILS	0,129	0,304	0,127	0,129	0,133	0,010
FM radio	0,102	0,518	0,045	0,143	0,224	0,068
TV VHF/TDAB/Mar	0,101	0,195	0,099	0,102	0,104	0,006
TETRA PMR	0,020	0,165	0,018	0,019	0,026	0,009
Def/Marine PMR	0,025	0,029	0,025	0,026	0,027	0,001
UHF TV Digital	0,068	0,148	0,062	0,069	0,095	0,012
WIND800DL / LTE	0,027	0,312	0,011	0,016	0,136	0,053
VF800DL / LTE	0,025	0,501	0,010	0,015	0,082	0,051
COS800DL / LTE	0,022	0,264	0,011	0,017	0,073	0,029
Microphones	0,011	0,017	0,011	0,011	0,012	0,001
WIND800UL / LTE	0,010	0,026	0,010	0,011	0,011	0,002
VF800UL / LTE	0,016	0,409	0,010	0,010	0,021	0,040
COS800UL / LTE	0,010	0,022	0,010	0,010	0,011	0,001
GSM-R	0,013	0,015	0,013	0,014	0,014	0,001
COS900UL / GU	0,010	0,013	0,010	0,010	0,011	0,001
WIND900UL / GU	0,011	0,069	0,010	0,010	0,012	0,007
VF900UL / GU	0,021	0,534	0,012	0,013	0,015	0,056
Def/GSM-R	0,012	0,122	0,010	0,011	0,013	0,009
COS900DL / GU	0,034	0,650	0,010	0,020	0,143	0,074
WIND900DL / GU	0,034	0,517	0,010	0,021	0,167	0,066
VF900DL / GU	0,037	0,611	0,013	0,027	0,130	0,068
Nav/GPS/SAT	0,077	0,171	0,076	0,078	0,080	0,006
WIND1800UL	0,016	0,468	0,012	0,013	0,014	0,037
VF1800UL	0,052	0,947	0,017	0,022	0,237	0,112
COS1800UL	0,021	0,043	0,020	0,021	0,022	0,001
Wireless Micr	0,016	0,059	0,016	0,016	0,018	0,003
WIND1800DL	0,032	0,441	0,015	0,027	0,100	0,047
VF1800DL	0,051	0,525	0,020	0,050	0,193	0,066
COS1800DL	0,063	1,289	0,025	0,058	0,208	0,103
DECT	0,023	0,110	0,022	0,023	0,025	0,006
COS1900TDD	0,010	0,013	0,010	0,010	0,011	0,001
WIND1900TDD	0,010	0,012	0,009	0,010	0,010	0,001
VF1900TDD	0,010	0,016	0,009	0,010	0,011	0,001
VF2100UL/UMTS	0,025	0,209	0,020	0,021	0,040	0,021
WIND2100UL/UMTS	0,018	0,219	0,015	0,015	0,017	0,020
COS2100UL/UMTS	0,018	0,035	0,018	0,019	0,019	0,001
Space Research	0,062	0,067	0,061	0,063	0,064	0,002
VF2100DL/UMTS	0,051	0,314	0,026	0,047	0,159	0,052
WIND2100DL/UMTS	0,035	0,261	0,019	0,028	0,117	0,038
COS2100DL/UMTS	0,058	0,782	0,024	0,044	0,226	0,090
Space Res / IMT	0,103	0,120	0,102	0,105	0,108	0,003
WiFi/RFID	0,067	0,211	0,064	0,066	0,073	0,013
Fixed/Sat Mob	0,028	0,034	0,027	0,028	0,029	0,001
VF2600UL/LTE	0,031	0,039	0,030	0,031	0,032	0,001
COS2600UL/LTE	0,037	0,041	0,037	0,038	0,039	0,001
WIND2600UL/LTE	0,031	0,075	0,029	0,031	0,032	0,005
Links/Def	0,015	0,018	0,015	0,016	0,016	0,001
COS2600TDD	0,029	0,033	0,029	0,030	0,031	0,001
VF2600TDD	0,029	0,034	0,029	0,030	0,031	0,001
Links/Def	0,015	0,019	0,015	0,016	0,017	0,001
VF2600DL/LTE	0,030	0,053	0,029	0,030	0,031	0,002
COS2600DL/LTE	0,041	0,185	0,037	0,038	0,062	0,014
WIND2600DL/LTE	0,040	0,401	0,030	0,031	0,081	0,045
Radar/Meteo rad	0,121	0,129	0,120	0,123	0,126	0,003
BROADBAND	**0,411**	**1,871**	0,305	0,437	0,777	0,181

Rest Urban-Rural areas: In Table 3.3, the electric field strength (E) from 54 different services is presented. Based on these results (average value), we may conclude the contribution of each source to the total radio exposure Defense, Military, and Meteorological systems (27-87.5 MHz) contributed as predominant sources with 31.1% (average value). Radio FM and TV signals (87.5-108, 108-410, and 470-790 MHz) were at a second level with an average of 30.9% of the total ER (5,8% and 25,1%, respectively). Mobile Communications (DL emissions) contributed 12.2% ranging from 2.6% to 90.7%, while 75% of mobile RF cases were below 13.2%. Analyzing the mobile sector, we found that the 900 MHz signal was the predominant source with an average value of 3.3% contribution to the total ER. Wi-Fi (2.4 GHz) signals were very low, with a 1.6% average contribution. (Fig. 3.5)

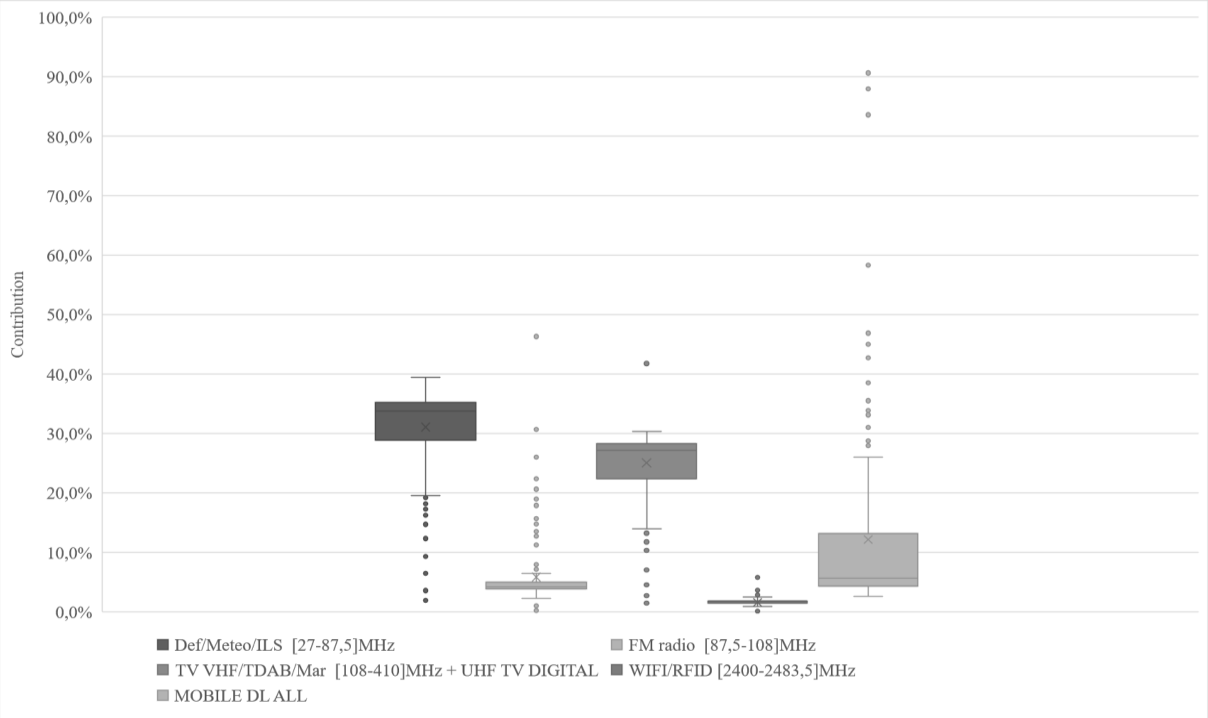

Figure 3.5. Box and Whisker plot of the contribution of RF sources in the total ER in the rest of Greece. Min and Max (Whisker) and the interquartile range (Q1, median, average, and Q3) are illustrated. ER = exposure ratio; RF = radiofrequency.

Table 3.3 shows the average electric field strength for each band and the broadband value for Rest urban / rural areas (376 spots).

Table 3.3. Average electric field strength (V/m) per service band in Rest of Greece (values out of 376 points of measurement).

Service / Electric Field (V/m)	AVERAGE	MAX	25TH	75TH	95TH	SD
Def/Meteo/ILS	0,137	0,253	0,124	0,129	0,245	0,034
FM radio	0,057	0,235	0,043	0,054	0,103	0,026
TV VHF/TDAB/Mar	0,107	0,199	0,096	0,101	0,192	0,027
TETRA PMR	0,020	0,104	0,018	0,019	0,035	0,010
Def/Marine PMR	0,026	0,050	0,024	0,025	0,047	0,007
UHF TV Digital	0,064	0,120	0,058	0,061	0,114	0,016
WIND800DL / LTE	0,018	0,178	0,010	0,019	0,054	0,019
VF800DL / LTE	0,014	0,077	0,010	0,015	0,033	0,008
COS800DL / LTE	0,019	0,236	0,011	0,018	0,049	0,027
Microphones	0,012	0,024	0,010	0,011	0,020	0,003
WIND800UL / LTE	0,011	0,023	0,010	0,011	0,020	0,003
VF800UL / LTE	0,013	0,125	0,009	0,010	0,019	0,013
COS800UL / LTE	0,011	0,021	0,009	0,011	0,019	0,003
GSM-R	0,014	0,027	0,013	0,014	0,026	0,004
COS900UL / GU	0,011	0,021	0,009	0,010	0,019	0,003
WIND900UL / GU	0,015	0,237	0,009	0,010	0,047	0,023
VF900UL / GU	0,019	0,343	0,011	0,013	0,023	0,042
Def/GSM-R	0,012	0,030	0,010	0,011	0,020	0,004
COS900DL / GU	0,029	0,581	0,010	0,028	0,080	0,058
WIND900DL / GU	0,021	0,212	0,010	0,022	0,053	0,023
VF900DL / GU	0,033	0,245	0,012	0,039	0,101	0,036
Nav/GPS/SAT	0,081	0,152	0,073	0,077	0,146	0,021
WIND1800UL	0,013	0,025	0,012	0,013	0,024	0,003
VF1800UL	0,023	0,280	0,016	0,017	0,034	0,029
COS1800UL	0,022	0,112	0,020	0,021	0,039	0,008
Wireless Micr	0,017	0,042	0,015	0,017	0,031	0,005
WIND1800DL	0,028	0,526	0,015	0,028	0,070	0,043
VF1800DL	0,033	0,194	0,019	0,039	0,079	0,024
COS1800DL	0,059	1,495	0,024	0,058	0,137	0,120
DECT	0,026	0,513	0,021	0,023	0,041	0,035
COS1900TDD	0,010	0,021	0,009	0,010	0,019	0,003
WIND1900TDD	0,010	0,020	0,009	0,010	0,018	0,003
VF1900TDD	0,010	0,020	0,009	0,010	0,018	0,003
VF2100UL/UMTS	0,022	0,069	0,019	0,021	0,038	0,008
WIND2100UL/UMTS	0,016	0,041	0,014	0,016	0,029	0,005
COS2100UL/UMTS	0,020	0,046	0,017	0,019	0,034	0,005
Space Research	0,075	0,241	0,059	0,062	0,229	0,049
VF2100DL/UMTS	0,037	0,214	0,025	0,044	0,079	0,025
WIND2100DL/UMTS	0,030	0,334	0,019	0,032	0,057	0,031
COS2100DL/UMTS	0,052	1,036	0,023	0,047	0,142	0,091
Space Res / IMT	0,103	0,127	0,098	0,105	0,121	0,007
WiFi/RFID	0,064	0,141	0,061	0,064	0,074	0,010
Fixed/Sat Mob	0,030	0,062	0,026	0,028	0,057	0,009
VF2600UL/LTE	0,033	0,075	0,029	0,031	0,072	0,012
COS2600UL/LTE	0,038	0,061	0,036	0,038	0,057	0,006
WIND2600UL/LTE	0,030	0,045	0,029	0,030	0,041	0,004
Links/Def	0,019	0,061	0,014	0,016	0,055	0,012
COS2600TDD	0,031	0,059	0,028	0,030	0,055	0,008
VF2600TDD	0,031	0,059	0,028	0,030	0,056	0,008
Links/Def	0,020	0,085	0,014	0,016	0,068	0,016
VF2600DL/LTE	0,032	0,062	0,028	0,030	0,056	0,009
COS2600DL/LTE	0,058	0,347	0,035	0,039	0,233	0,061
WIND2600DL/LTE	0,030	0,076	0,029	0,030	0,033	0,004
Radar/Meteo rad	0,118	0,125	0,115	0,121	0,123	0,004
BROADBAND	**0,363**	**1,921**	0,296	0,355	0,588	0,160

4) Comparison of the RF exposure levels in metropolises and the rest of Greece:

It is of great scientific interest to check if the RF background in an urban environment is different from the RF background met in rural areas. The electric field values for the two populations (metropolises and rest Greece) have been checked using the Kolmogorov-Smirnov and Shapiro-Wilk test for normality, concluding that the case is not a typical Normal distribution (it approaches, but there is no clear result). Mood's median test is a nonparametric test to compare the medians of two independent samples. It is also used to estimate whether the median of any two independent samples is equal. Non-parametric tests are statistical tests without parameters. For these types of tests there is no need to characterize the population's distribution based on specific parameters. Nonparametric tests do not make assumptions about a specific distribution. Although the Mood's median test does not require normally distributed data, that does not mean that it is assumption free. The assumptions of Mood's median test are that the data from each population is an independent random sample, and the population distributions have the same shape. If the p-value of the test is less than the agreed "Alpha risk of 5 percent (0.05)", the null hypothesis is rejected and at least one significant difference can be assumed. The null hypothesis, H_0, confirms that: The samples come from the same distribution, or there is no difference between the medians of the selected groups. The alternative hypothesis, H_a, supports that: The samples come from different distributions (i.e., at least one median is different). In our study, a median test (Mood's test) is performed for the broadband electric field strength E (0.34 V/m for metropolises and 0.30 V/m for the rest of Greece) and the total ER (0.078×10^{-3} for metropolises and 0.062×10^{-3} for the rest Greece). P-value lies under the critical value of 0.05 for both cases, which means that the medians are statistically significantly different.

3.5 Discussion

The discussion is divided into three (3) sections: The first section discusses the results, while the second section evaluates how the existing levels of RF technology can leave enough safe space for the 5G installation in Greece. In the third section, we discuss the people's perception of the EMF fields, especially mobile base station emissions.

1) Radiofrequency exposure in Greece (from 27 MHz to 3000 MHz)

In both cases (Metropolitan areas and the rest of Greece), the mean and median values of broadband electric field strength fall in the background levels, well below the ICNIRP's 2020 guidelines. No value out of 1000 measurements exceeded the safety limits. Following a median test analysis (Mood's median test) for the medians of the broadband electric field strength and the ER, we rejected the "null hypothesis" that the two values are not statistically different. Therefore, the medians for both the electric field and ER are different. A bioelectromagnetic research in Japan by Onihi T., [59], focused on human protection from EMF fields showed that E-field exposure in an urban environment is 7 dB higher than in suburban areas. According to Manassas et al., 2012 [60] and their measurements performed in Greece, the authors concluded that there is a statistically significant difference between the urban (median electric field: 1.1 V/m) and the rural environment (median electric field: 0.3 V/m) following the non-parametric statistical test (Kruskal–Wallis) to compare the two different conditions. Based only on mathematics, we may be concerned about these differences and how the RF fields are distributed in the two cases. But considering the significant uncertainty for ER (~50%) and the extremely low levels of RF fields' strength, we should separate statistical from practical significance. In practice, the medians could be considered as not different. Due to the denser mobile networks, one could expect higher RF exposures in crowded towns. Base stations are installed closer to schools, hospitals, and other locations of sensitive land use. On the other side, in rest urban or rural areas, the lower capacity requirements (fewer customers) allow the installation of fewer base stations, most of them at large distances from people's residences. Based on the field propagation theory, a base station should increase its power when there is a higher distance between the antenna and the receiver (customer) to overcome the "inverse square low” attenuation. This leads to a rural network of higher output power than the urban one. As a result, in a metropolitan area, we meet dense installations, but less emitted power, while in rural cases, we find fewer base stations but higher output power. Finally, according to the results, the two areas exhibit almost the same RF exposure levels, considering the uncertainty. The differences are practically negligible. In metropolitan areas, the average mobile sector’s contribution is a little higher than in the rest of Greece (14.9 % vs. 12.2 %). This is expected due to the reason mentioned above (denser networks). Average FM emissions are almost triple in metropolitan areas (14.9 % vs. 5.8 %). This is expected due to closer distances between FM antennas and points of measurement. TV signals are found in second place for all of Greece (average values: 21.3% in metropolitan areas vs. 25.1 % in the rest of Greece) due to the high power used even if they are located in the mountains (antenna parks), far away from habited areas. Defense and meteorological systems (<87.5 MHz) are the predominant RF source in both areas. In theory, Wi-Fi antennas use extremely low power (~0.1-1 Watt, operating at 2.4 or 5 GHz). The antenna gain is ~6dBi as stated in ITU-T, 2014 [61]. The extremely low power permits indoor installation without any specific protection measures. Most devices (routers) declare a safety distance of 20 cm in their manuals. In our study, Wi-Fi exposure levels at 2.4 GHz exhibit almost the same contribution to the total field for both areas (average values: 1.4% for metropolitan and 1.6 % for the rest of Greece). Following Ramirez-Vazquez et al., 2020 [62] study, the average Wi-Fi exposure in university areas was 28.82 $\mu W/m^2$. In our study, the average Wi-Fi emission was 12.34 $\mu W/m^2$ (metropolitan areas) vs. 11.02 $\mu W/m^2$ (rest of Greece). A similar analysis [63] to the present one was performed by the French National Agency of Frequencies (ANFR), published in 2018 in France. During this study, 2591 measurements were carried out. The median electric field strength was 0.36 V/m, while 80% of the results were below 1 V/m. The present study’s median electric field strength was 0.32 V/m for all of Greece, close to the French result. Moreover, 75% of all measurements were below 0.42 V/m. According to Chiaramello et al., 2019 study [64], mean RF exposure in schools, universities, and kindergartens ranges from 0.07 to 0.54 V/m. Based on Verloock et al., 2014 study [65], the mean electric field strength in schools' locations was 0.20 V/m. In a Korean study by Kim et al., 2010 [66], the highest exposure level corresponds to 0.15% of the ICNIRP's guidelines. The highest exposure is 0.13% of the same guidelines in our study. A higher value (but also considerably lower than the internationally adopted limits) is met in Kim et al., 2014 study [67]. The highest RF exposure in densely populated areas was 7.1% of the guideline's limits. In the Greek study Christopoulou et al., 2019 [68], concerning RF exposure in playgrounds sites, the median values for the urban environment were 0.244 V/m and 0.229 V/m in the suburban. Gajsek et al.'s 2015 results [69] showed that the mean value of electric field strength ranged between 0.08 V/m (urban, Austria) and 1.80 V/m (close to microcells, UK). A large study in Belgium and Greece, completed in 2013 by Vermeeren et al., 2013 [70], found that the average exposure in schools was 0.40 V/m in Greece and 0.39 V/m in Belgium. A similar study performed in Amsterdam schools by van Wel et al., 2017 [71], exhibited an average power density of 70.5 $\mu W/m^2$ (or 0.16 V/m). Therefore, the results presented in this study are in accordance with other similar conclusions.

2) Expected 5G exposure in Greece

As already mentioned, Greek legislation adopts stricter general public safety limits than ICNIRP. To assess the "remaining" space for the 5G exposure that is going to be superimposed, we should evaluate the RF levels based on the Greek limits (60% of the ICNIRP 1998 level):

Metropolitan areas (Athens and Thessaloniki): Evaluating the compliance with the Greek stricter limits, the total maximum ER (maximum exposure recorded) is 464 times below the limit, with a median value of 7.7×10^3.

Rest Urban-Rural areas: The total maximum ER for the rest urban/rural areas is 547 times below the limit, with a median value of 9.7×10^3 below the limit.

Therefore, the maximum exposure levels based on the legacy technologies (2G, 3G, 4G) are very low compared to the stricter Greek safety limits. In 5G technology, the use of Massive MIMO antennas increases the nominal base stations' emitted power. Following the ANFR, 2020 study [72], a 4G base station emits a nominal power of 60 W and 18 dBi antenna gain, while a 5G antenna emits a nominal power of 200 W with 24 dBi gain. Beamforming 5G techniques described in Chiaraviglio et al., 2018 [73] study, and the increased attenuation in the air for 3.5 GHz compared with lower bands (-4 dB in the air for the 4G band and -13.5 dB for the 5G band according to ANFR), contribute to a considerable decrease of the exposure. Time Division Duplex (TDD) technology also imposes a -1.25 dB decrease in the output power of a 5G antenna, as in the time-division mode, not all the time slot is used for emission but a fraction of it. According to the French organization, the two cases mentioned above produce almost the same electric field strength at a 100 m distance (1.7 V/m exposure from the 4G antenna and 1.8 V/m from the 5G one). As a result, it is not expected to face problems with the safety limits compliance in Greece. But the horizontal safety distances will inevitably be increased in each installation location. Updated calculations should be performed to permit access very close to a new 5G base station. Additional fencing may be needed on many roof terraces where the base stations are usually installed. Other countries also exhibit stricter limits (Italy, Belgium, and others). Stricter limits, without any scientific background basis, could prevent the rollout of 5G increasing people's concern. For that reason, the safety guidelines should be harmonized.

3) EMF perception and public concern

EC Eurobarometer study [74] reports an analysis of 2010 survey results to assess the public perception of the potential EMF health effects. A percentage of 35% and 33% of the population believe that high voltage power lines and mobile phone masts (antennas), respectively, impact their well-being and health. Countries exhibiting the most significant percentages are Italy (79%) and Greece (63%). Only 20% of EU participants support that they have received enough information on the potential health effects of EMFs. Television (55%) and newspapers/magazines (38%) are the most frequently mentioned sources of information, followed by the Internet (19%). Nowadays, the internet could reach a much higher percentage due to its extensive penetration in homes. In Greece, television represents 73% of respondents. Authorized organizations score below 6%, unfortunately. The results also show that 58% of respondents do not believe that public authorities protect them from the detrimental use of EMFs. The highest percentages on this parameter are recorded in Greece (75%), Latvia (72%), Lithuania (71%), and Slovenia (70%). Public Authorities and Universities should play an essential role in supporting governmental organizations during the 5G era.

3.6 Conclusion

Due to the considerable EMF public concern in the Greek society and the controversy in the scientific community, it is more than necessary to perform EMF exposure assessment periodically, following up on the rapid changes in the EMF environment. In the Greek National EMF research program (EDBM34) frame, 1000 measurements of RF field exposure have been carried out in Greece in locations of sensitive land use (schools, universities, kindergartens, hospitals, elderly homes, and playgrounds). The compliance with ICNIRP 1998, ICNIRP 2020, and the strictest Greek safety guidelines was examined and confirmed in all cases. Moreover, the results are in accordance with the international bibliography. The domination of TV, FM signals, and defense-military or meteorological systems' emissions was concluded. No measurement exceeded ICNIRP's limits. Protection of the general public and children is ensured at all measurement locations. Considering the public concern about exposure to electromagnetic fields, harmonization of exposure limits among nations might help reduce anxiety. The study should be repeated, including the 5G technology rollout in Greece in the next two years.

Chapter 4: 5G Principles and Human Exposure

4.1 Introduction

5G technology stands for the 5th Generation technology in mobile communications. South Korea was the first country to adopt 5G on a large scale was, in April 2019. Introduced commercially in Japan by NTT DoCoMo in March 2020, with an initial maximum data rate of 3.4 Gbps (3400 Mbps). 1.5 billion 5G connections are recorded in 2023 with a provision of 5 billion connections in 2030. 87% of Europeans will exploit the benefits of this technology in 2030, 91% in North America. In Europe there is an 81% smartphone adoption in 2022 with a projection of 91% in 2030 based on GSMA "The Mobile Economy 2023" report (Fig. 4.1). Data traffic is moving fast from 3G and 4G to 5G. In Fig. 4.2 (from ABI Research) it is obvious that 5G will be the lead technology for data services worldwide in 2025.

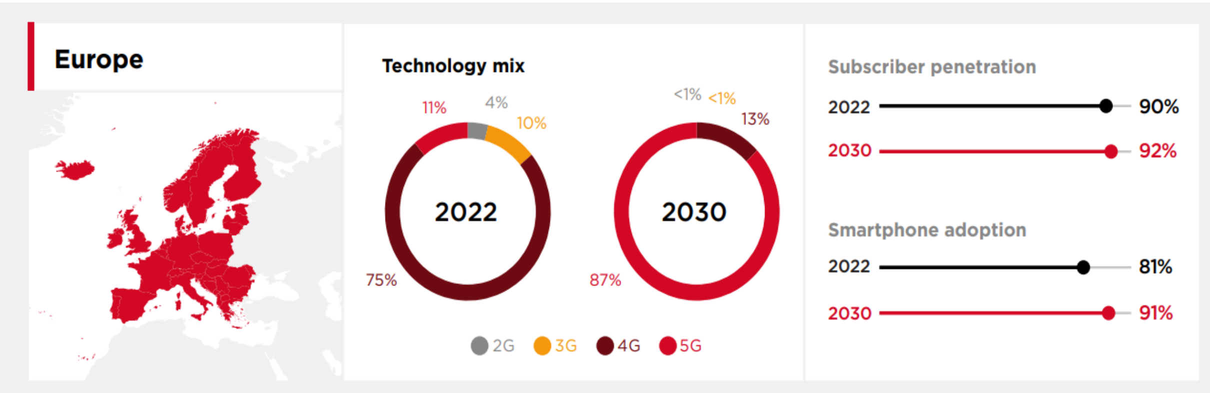

Figure 4.1. Technology usage in 2022 and projection in 2030 (source GSMA)

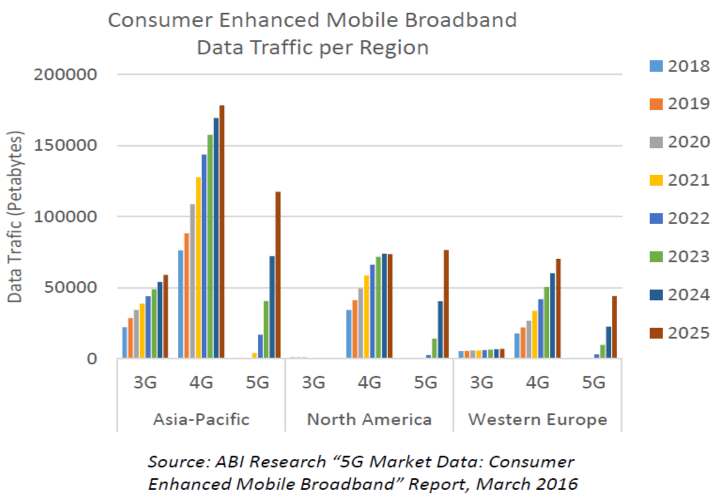

Figure 4.2. Data traffic worldwide since 2018 and projected to 2025. %g is the leading technology. 3G is getting shutdown (source: ABI Research)

4.2 Basic Principles of 5G

5G technology targets to the following 3 pillars that are analyzed below (Fig. 4.3).

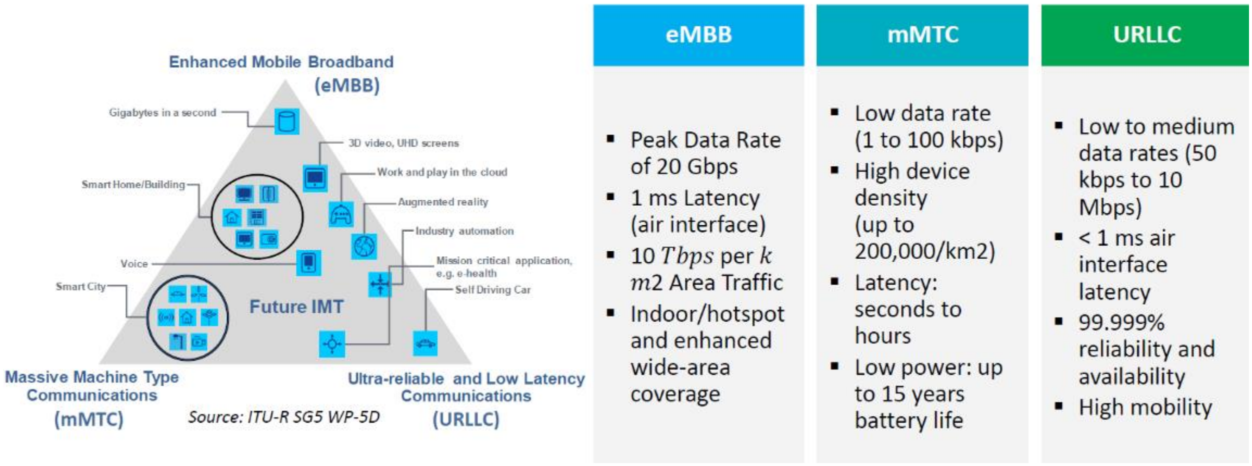

Figure 4.3. 5G pillars: Extremely high data speeds (Enhanced Mobile Broadband), Massive Machine Type Communications, and very Low Latency in data transfer (Reliability in communications). Source ITU-R. SG5 WP-5D.

5G Pillars:

a) **Enhanced Mobile Broadband (eMBB):** 5G technology exploits the mmWave spectrum (see next paragraph 2) with wider bandwidths providing considerable capacity, thus higher data rates. The peak data rate could be theoretically from 1 to 20 Gbps (instead of 150 Mbps of the 4G technology and 15 Mbps of the 3G). As a conclusion, enhanced mobile broadband (eMBB) is the first service provided by 5G technology. The user experiences high-definition video streaming such as 4K resolution, immersive augmented reality (AR), and virtual reality (VR) on the go. Below (Fig. 4.4), we present an example of the service speed provided by different technologies (time to download a high-resolution movie) from OFCA Hong Kong ("*Office of the Communications Authority is the executive arm of the Communications Authority (CA) as well as a trading fund department of the Government of the Hong Kong Special Administrative Region"*). Its vision is to support the Communications Authority in fulfilling its vision that Hong Kong has the world-class communications services to meet the challenges of the information age.

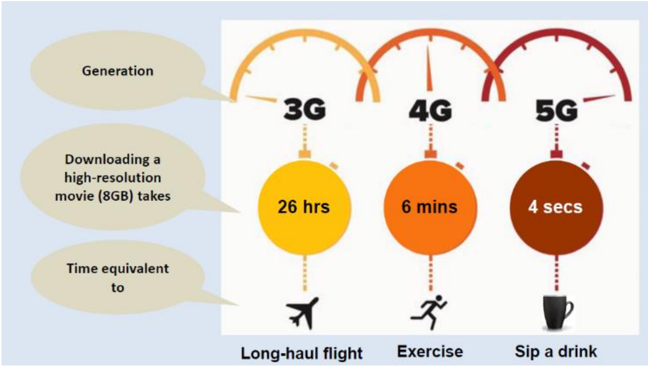

Figure 4.4. Time to download a high-resolution movie with the 3 different mobile technologies – 3G, 4G, and 5G (Source: OFCA)

b) Critical Communications (CC) and Ultra Reliable and Low Latency Communications (URLLC): Extremely high reliability is expected. To remote control a process (for example a surgery), a reliability of 99,9999% is expected, with a user experienced data rate up to 100 Mbps and an air interface latency < 1 ms (see "Definitions" below). 5G technology exploits the higher bandwidths in higher frequencies used in the electromagnetic (EM) spectrum (Fig. 4.5)

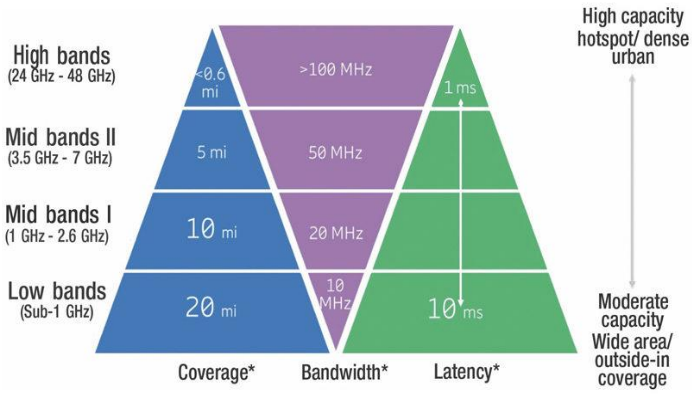

Figure 4.5. Higher frequency bands provide wider carrier bandwidths, thus higher data rates, and lower latency.

Source: https://broadbandlibrary.com/5g-low-latency-requirements/

Definitions:

***Coverage**: The geographic area that can be served by a specific antenna

***Bandwidth**: Every signal (data) is transferred on a specific frequency (carrier, f_c). In radio communications, a sideband (SB) is a band of frequencies higher than or lower than the f_c, as a result from the modulation process. Modulation of a carrier signal normally results in two mirror-Figure sidebands (f_c – SB, f_c +SB). The sidebands carry the information transmitted by the radio signal. The signal components above the carrier frequency constitute the upper sideband (USB = f_c +SB), and those below the carrier frequency constitute the lower sideband (LSB = f_c – SB). Bandwidth (BW) is defined as the difference (the width) between the USB and LSB. The larger the BW the more data transferred in a sec.

***Latency**: Latency refers to the time delay between the cause and the effect of some physical change and in telecommunications defines the responsiveness of the network. It measures the delay of transferring data to and from the user's device [75]. In the example below, a car is receiving the information to stop from a 4G and a 5G network (Fig.4.6). The end-to-end time represents the delay (the latency) for the information to be transferred. Due to the higher delay in 4G the car needs 60 cm in 4G VS 7 cm in 5G to be fully stopped.

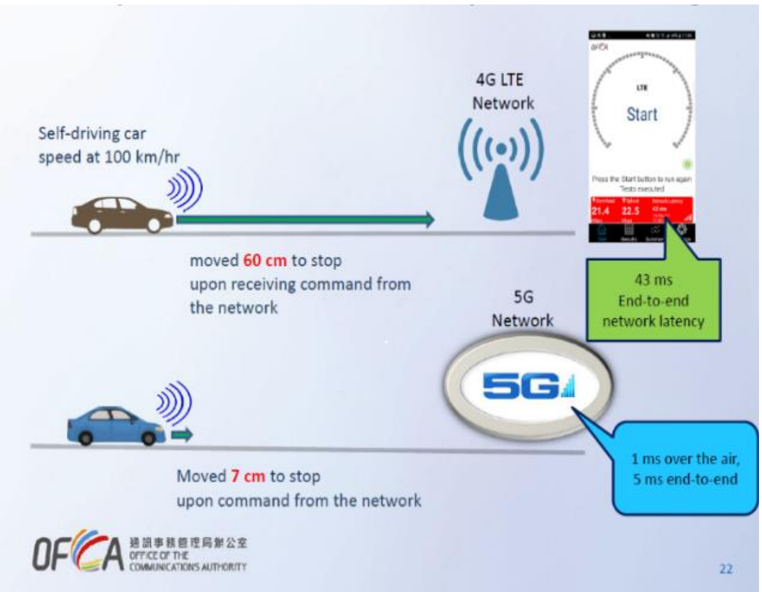

Figure 4.6. Comparison of the end-to-end information transfer in the network concerning a self-driving car. (Source OFCA)

c) Massive Machine Type Communications - Internet of Things (IoT): The Internet of Things (IoT) describes the wireless network of physical objects - "things", such as devices, machines, and appliances, that are embedded with sensors, software, and other technologies, for the purpose of connecting and exchanging data with other devices and systems over the internet. These include PCs, tablets, wearable health monitors, wireless inventory trackers, smart factory equipment, vehicles and other devices and machines equipped with IoT connectivity. Machine-to-machine (M2M) refers to the activation of communication between two or more machines with limited human intervention. Monitors and sensors can also be connected wirelessly allowing wireless applications in health, water, electricity, and agriculture (Fig. 4.7).

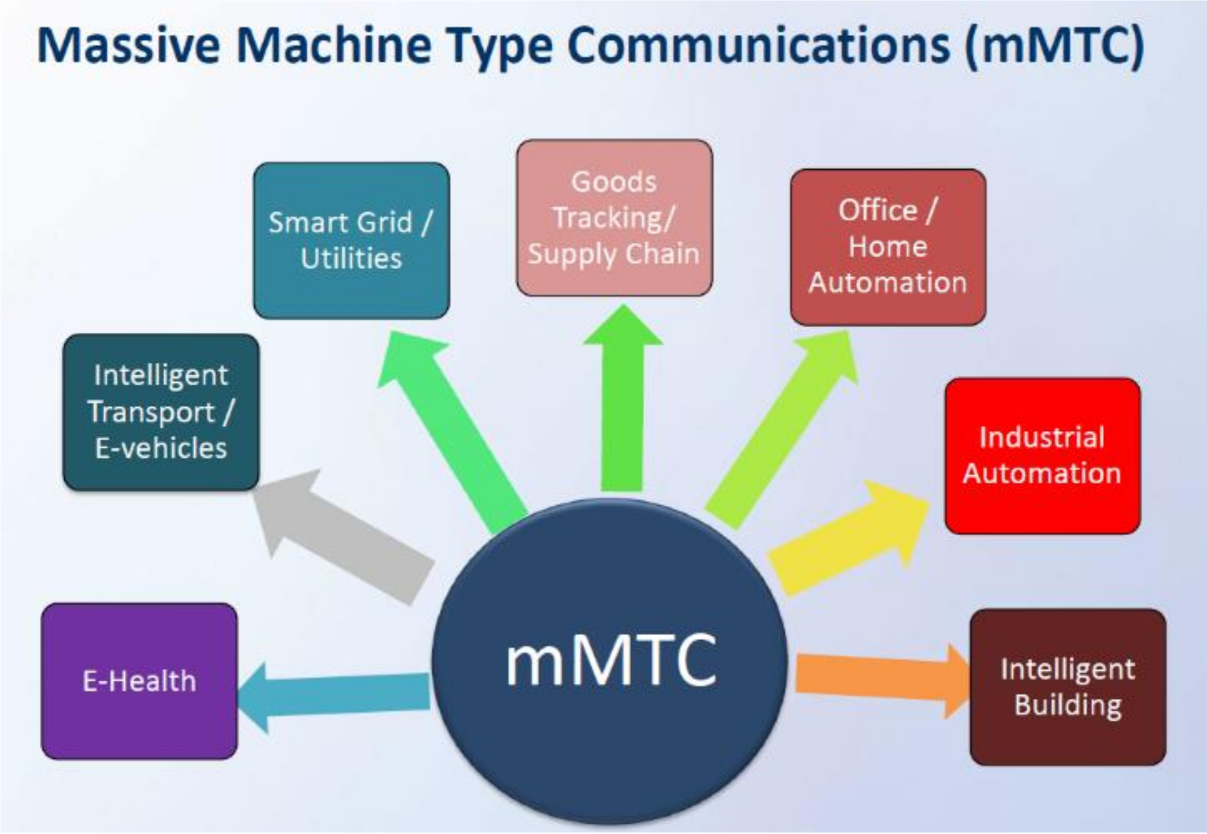

Figure 4.7. Machine to Machine communication can be implemented in many daily activities and services such as Health, Home automation etc. Source OFCA

Standardization of 5G: The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as “Organizational Partners” providing their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. 3GPP specifications cover cellular telecommunications technologies, including radio access, core network and service capabilities, The 3GPP specifications also provide hooks for non-radio access to the core network, and for interworking with non-3GPP networks. Standard release 17 is currently in use describing the operation of the 5G technology.

4.3 The Spectrum of 5G

Each mobile base station (BS) carries a number of antennas trying to fulfill two main targets: the *Coverage* and the *Capacity*.

Coverage is the geographic area within which the BS serves the customer needs. Based on the technical standards, a typical coverage radius of a BS installed in a rural environment is 1 to 5 kilometers (cell towers). Concerning dense urban environments, a typical BS (cell mast) covers up to 1 km distance before transferring the user's connection to another nearby cell site (handover process). There are several factors that impact the coverage radius of a macro base station (*a BS is characterized as "macro", when its coverage expands in a large geographic area as described above up to kms, whereas a "micro" is a BS that covers locally ad hoc needs such as a crowdy shop, a town square, a busy road, a football stadium, a concert place, etc*). One important factor is the spectrum used (the others are: the BS power, the geographical relief, the number of customers served, and the quality of the customer's demands). The higher the frequency used, the more difficult it is for the EM field to penetrate building materials, to overcome obstacles, and the more attenuated in the air. "Path loss" refers to the attenuation of electromagnetic waves along the path from transmitter to receiver. It is usually expressed in decibels (dB). Thus, high frequencies cannot reach large distances from the BS. In the following Fig. 4.8, we may see the attenuation of the EM field (in db / km) versus the frequency (in GHz) in different air conditions [76]. As a result, to ensure good coverage conditions, we should use low frequency bands. For example, in mobile technology, coverage is achieved using 800, 900, 1800 MHz. Higher bands have other characteristics providing a bigger data transfer rate but in shorter distances (see Capacity). Moreover, materials such as buildings materials, exhibit high attenuation rates. The effect of frequency on path loss can be exemplified by measuring signal strength between two antennas 500m apart in line-of-sight. At the extremes, compared with a signal on 800MHz, a 39GHz signal has approximately 34dB (around 99.96 percent) more free-space path loss.

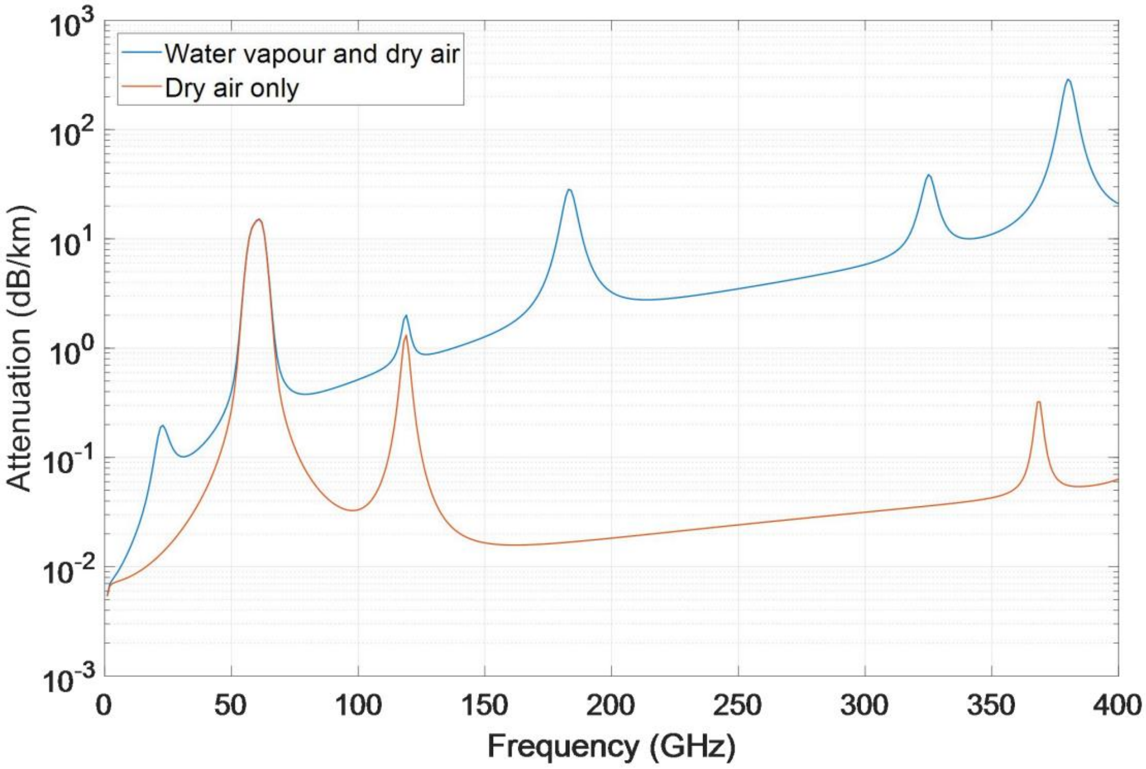

Figure 4.8. Frequency dependent attenuation of EMF radiation in standard atmosphere (1013 mbar, temperature 15 °C, water vapor density of 7.5 g/m^3*). Han et al., 2019 [76]*

Capacity (C) is the ability of the network (a BS) to transfer information (data, measured in bits) at a given point in a specific time frame (sec). It is the maximum data transfer limit that can be achieved, measured in bits/sec. Based on SHANNON theory (Equation 1):

$$C = B * \log_2\left(1 + \frac{S}{N}\right) \qquad (1)$$

Where:

B = Bandwidth

S = Signal power

N = Noise power

As a conclusion the Capacity informs on the speed that the customer experience on his device (Mbps = Megabits per sec or Gbps = Gigabit per sec). The Capacity depends on the spectrum band that is used by the device. The higher the frequency band, the larger the Bandwidth used and the higher the Capacity achieved based on Shannon law. 5G millimeter-wave (above 24 GHz) will provide much higher bandwidths than 5G in few GHz (3.5 GHz or 6 GHz). In the following Fig. 4.9, we may see a mechanical analogue with road traffic and the improvement when many highway lines (this is the larger bandwidth in use) are available.

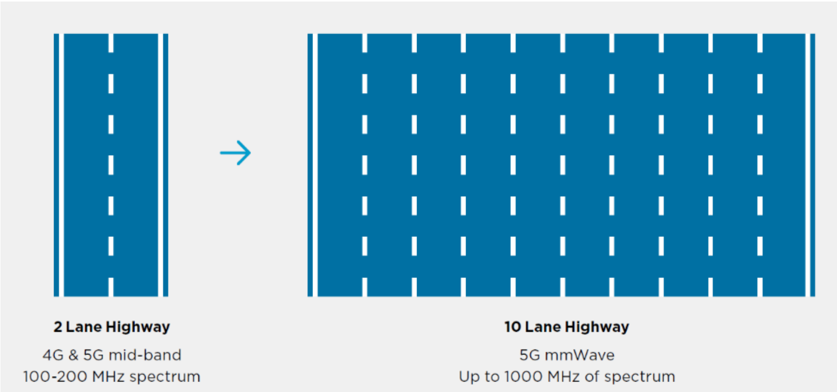

Figure 4.9. Larger bandwidth provides higher capacity, thus higher downloading speed to the user. Source: GSMA

Based on the definitions and characteristics of Coverage and Capacity, we may conclude that low frequencies are more efficient for coverage reasons (penetration ability) and the high frequencies for capacity purposes (larger bandwidths and data transfer rates).

The spectrum (see Fig. 4.10) used in 5G covers 3 bands: low, medium, and high bands (Tyrakis et al., 2023 [52]).

- Low band (600,700,800 MHz): Low band frequencies that are used for coverage reasons, especially in indoor coverage Bandwidth used is 10 MHz and the capacity achieved is 120 Mbps (peak value).

- Mid-Bands (2100, 3500-3700 MHz): These bands are used for both coverage and capacity reasons. The 3.4 to 3.8 GHz band is called C-band and can provide customers with very large bandwidths (i.e., 100 MHz), and very high speeds up to 1700 Mbps (peak value).

- High bands (mmWave): 5G may use very high frequencies in the range 24 to 40 GHz. This spectrum is called "millimeter-wave – mmWv" and is used for high data rates in applications such as Machine to Machine (M2M) communications, Internet of Things (IoT), and low latency services. Very large bandwidths are used up to 1 GHz and the capacity achieved can be up to 10 Gbps.

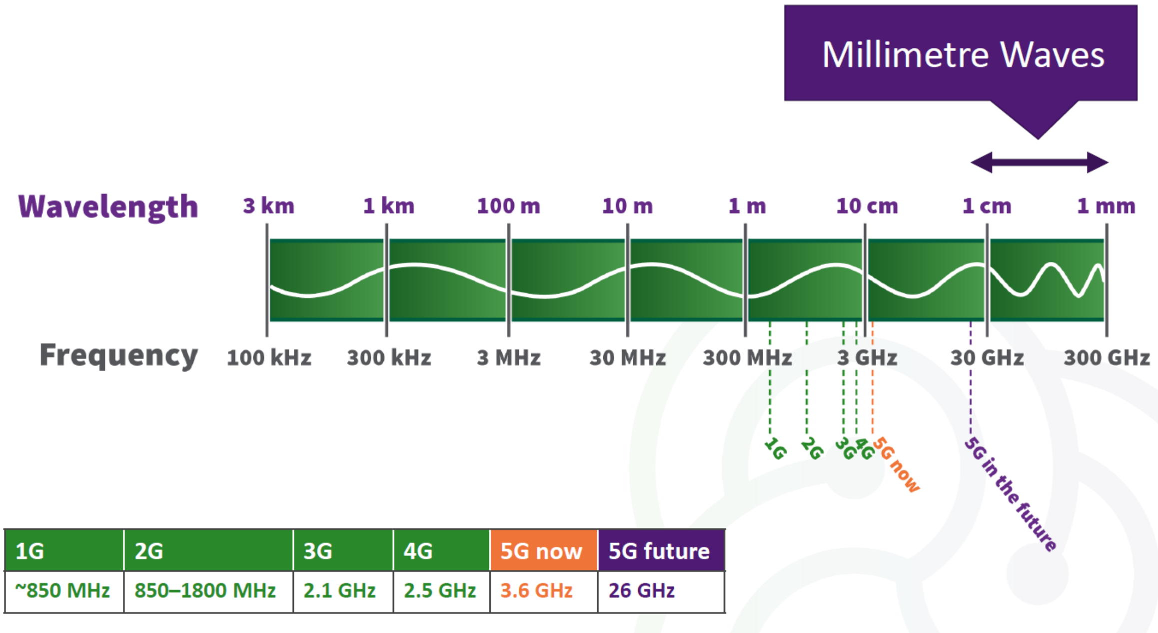

Figure 4.10. Slide by ARPANSA, Ken Karipidis, GSMA EMF Forum 2021.

4.4 Human Exposure to 5G Technology

4.4.1 Active MIMO Antennas and Beamforming

MIMO stands for Multiple Input Multiple Output technology used in antennas systems. Multiple antennas at the radio transmitter (output / antenna) and receiver (input / mobile device) are used to improve the performance of a wireless communication system by improving coverage conditions and the capacity of the system. The system performance is improved in 3 ways [77]:

a) **Spatial Multiplexing**: Spatial diversity is a technique in MIMO that reduces signal fading by sending multiple copies of the same radio signal through multiple antennas. This technique boosts data rates by sending the data in separate streams through spatially separated antennas. The main idea is the multiple channels that can be formed in scatterer-rich environments so that multiple data streams can be transmitted and recovered independently.

b) **Cyclic Delay Diversity**: Based on this technique, copies of the same data stream are sent by the antenna elements with a time delay to improve signal to noise ratio. Thus, the data rate is improved also. MIMO antenna with multiple (many) elements is efficient to use this technique.

c) **Beamforming**: Antenna beam is being processed to be transmitted – directed to a specific mobile device (receiver). The beam is narrow, and the energy is focused to the desired area. The process is also called spatial filtering. Co-polarized regularly spaced column arrays are used to form a desired pattern (shape). In the phased antenna array, it is assumed that the number of antenna elements and their spacing are fixed for each antenna. By controlling the RF signal phases and amplitudes feeding the antenna elements, it is possible to dynamically shape the overall radiated pattern. Unlike traditional antennas that could transmit and receive only on fixed radiation patterns, beamforming antennas dynamically shape their beam directions according to the location of their connected users. Thus, these antennas are often referred to as "beamformers." Beamforming antennas are unique in their ability to effectively reduce interference, improve the signal-to-interference-and-noise ratio (SINR) and deliver a significantly better end user experience. With the adoption of 6 GHz and mmWave frequency bands, beamformers are becoming an essential tool in mobile communications (Fig. 4.11)

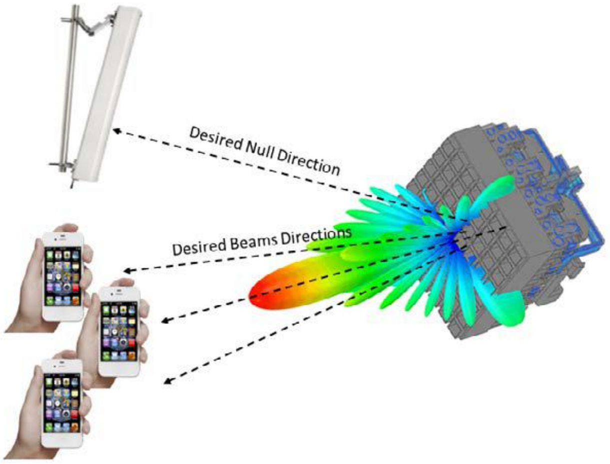

Figure 4.11. A MIMO antenna with beamforming capability. Multiple shaped narrow beams are directed to certain users. Source: Commscope, "Beamformers Explained", Dr. Mohamed Nadder Hamdy, PhD.

<u>Massive MIMO</u>

Massive MIMO stands for Massive Multiple-Input Multiple-Output. Antennas exhibit a very large number of antenna elements to improve spectral and energy efficiency, performance characteristics, while improving the user experience (high data rates). Massive MIMO or m-MIMO is a key building block of 5G technology, especially in the higher bands such as 3.5 or 3.7 GHz. Massive MIMO is expected to deliver up to 4-5x downlink (data rate from base station to mobile device) capacity gains compared to 2x2 MIMO, and enhanced coverage overcoming the propagation limitations (higher attenuation in the air as described in paragraph 2) of higher bands. Massive MIMO can be referred to 32x32, 64x64 or higher MIMO category. In Fig. 4.12 (presented in December 2017, Warsaw, Poland, by ITU) we may see the difference between a typical 4G antenna and a 5G MIMO antenna with beamforming effect.

Figure 4.12. 4G VS 5G MIMO antenna with beamforming. 4G beam covers an area with many receivers while the beamformer directs dedicated beams to users. Source: ITU (Poland, 2017 conference).

Benefits of using m-MIMO technology in 5G:

- Increases capacity: Up to 4-5 times the capacity in same bandwidth (theoretical expectation), due to the enhanced performance and the possibility to reuse radio resources when MIMO techniques are applied.
- Increases user performance: Higher user throughput can be achieved. Users, located far away from antenna almost at the edge of the cell (area) covered by the BS, can also benefit from the higher antenna gain and reduced interference levels of M-MIMO antennas.
- Reduces interference: M-MIMO powered base stations can purposely avoid transmitting towards directions where spreading interference would be harmful. Additionally, instantaneous beamforming drastically reduces the interference level between adjacent cells, as the chances of a beam to be focused on the direction of an unwanted user are low.
- Enhances coverage: Overcoming high bands propagation limitations, due to the higher antenna gain and the reduced interference level.
- New Radio (NR – 5G) enhancements: Additional benefits when applied to 5G are expected due to the optimization of beamforming procedures in NR. Estimations show a +20% capacity gain, +30% user throughput (data rate) and +8 dB coverage gain.

4.4.2 Realistic Maximum Power Level

As we have mentioned, MIMO technology is a key characteristic in 5G era to increase the capacity of cell, thus, to serve customers with very high speeds. Typical MIMO deployments are 8x8 (conservative), 32x32 (realistic), and 64x64 (supported in many countries). Of course, there are higher categories that can be used in the future (e.g., 128x128). It makes sense that a high MIMO antenna should emit with high power (e.g., 200 W). Legacy base stations could emit at 50 W (in demanding conditions) or less. This, will lead to higher safety distances (Fig. 4.13)

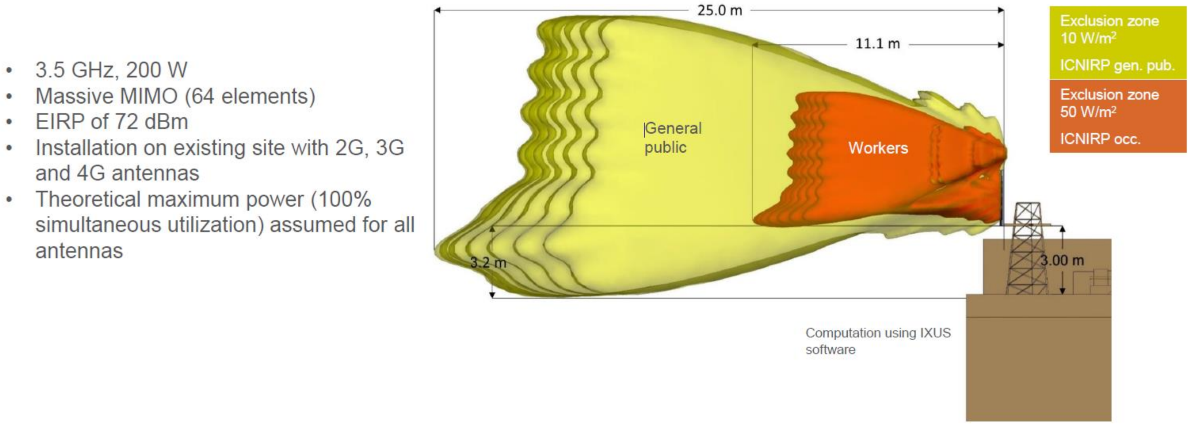

Figure 4.13. Safety distances from a typical 5G BS operating at C-band, on the top of legacy technologies, as presented by Christer Törnevik, Ericsson, ITU Workshop on 5G, EMF & Health, Warsaw, December 5, 2017.

A safety distance of 25m for the general public prevents most of the urban deployments in crowdy cities. Thors et al., 2017 [78], developed a statistical model that considers factors that keep the realistic power much lower than the theoretical. These factors are a) base station utilization (not all the capacity is used for 24 hrs.), scheduling time (the time and resources allocated to the users), distribution of user equipment (not all the beams are concentrated to a point), and time division duplexing (a portion of the time is used in downlink, thus in RF emission). Following this concept, and based on real measurements, it has been shown that 95% of the real maximum power used in a typical 5G BSs is under 15% of the theoretical maximum (Fig.4.14). According to the Swedish mode [78], even for a very high system utilization, the time-averaged realistic maximum was found to take values between 7% - 22% of the theoretical maximum. As a conclusion, according to the model, a 25% of theoretical maximum power for 8x8 array antennas, could be applied always.

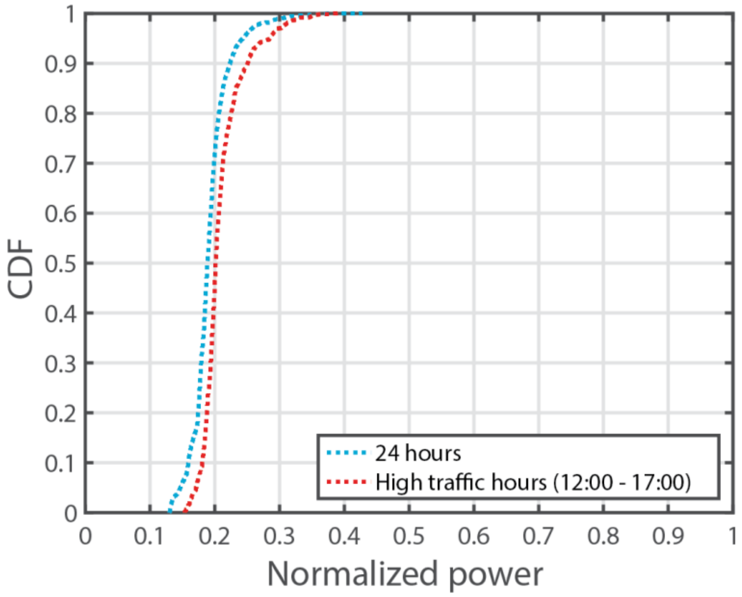

Figure 4.14. According to the model Output power levels at High traffic hours: the Mean power is 20.9, the Median is 20.1%, the 95th percentile is 28.5%, and the Max = 39.1% (study at Telia multi-technology sites in Sweden 2016).

In the next Figure 4.15, the safety distances could be reduced (from ~18m to ~8.5m) considerably if the realistic power is applied. This decrease gives the chance to many countries with strict safety limits (as Greece) to deploy 5G networks in urban environments.

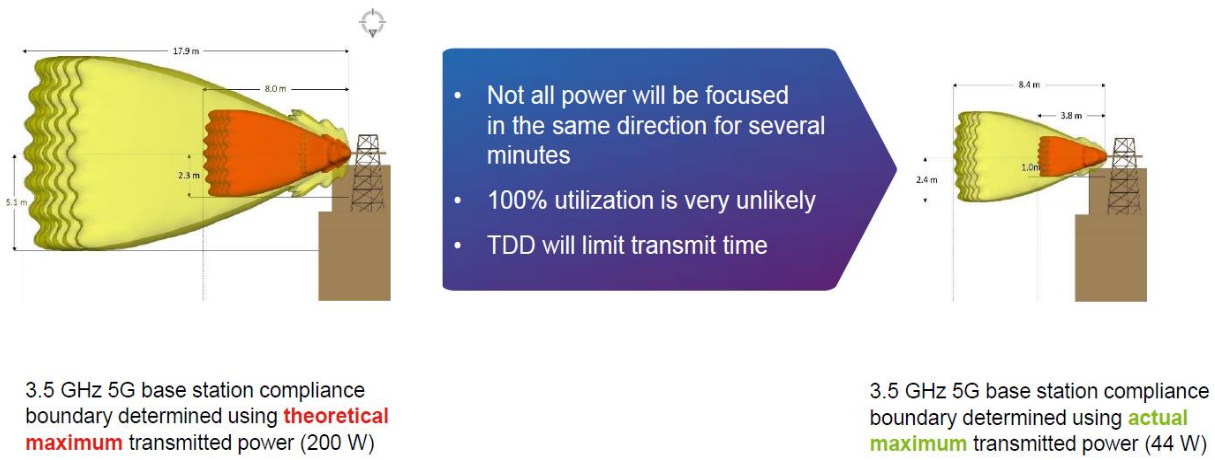

Figure 4.15. Safety distance of C-band operating BS, before and after the realistic model application. Christer Törnevik, Ericsson, ITU Workshop on 5G, EMF & Health, Warsaw, December 5, 2017.

4.4.3 5G Features Impact on the EMF Exposure

In this section we should focus on the differences induced by the 5G technology compared to the legacy systems. As mentioned in this chapter an important difference in the RF emission of 5G antennas is the beamforming that leads to directive beams to the user. MIMO is another new technology used by the 5G antennas. Low coverage (attenuation in air) and penetration capabilities (attenuation of high frequency EMF inside buildings) lead to the need for dense networks (more base stations to be installed) to keep high quality services to users. Moreover, the introduction 5G leads to the offload from legacy systems (traffic moves from 4G to 5G, 3G is closed down, etc). How do these new conditions affect the EMF exposure? Before providing real field measurements from international bodies and labs, we will present the theoretical approach [73]:

(a) **MIMO**: MIMO technology increases the radiated power as more antenna elements are in use. The higher the power used; the more exposure (electric field strength) may be recorded. Possible increase in RF exposure.

(b) **Beamforming**: Directionality control of the radiated power. The beam is directed to the selected area (user equipment). Possible decrease in RF exposure to areas with less or no traffic. Only the active user of a mobile device is affected.

(c) **Dense networks** (small cells): Dense networks means lower power emitted as the coverage area decreases. This is a rule of thumb for networks. Small cells exploit very low power to cover busy squares, stadiums, high traffic roads or limited neighborhoods with shop centers etc. On the contrary a macro base station that is targeting to cover a big area should emit at higher power contributing to higher exposures. Possible decrease of exposure in general. Possible increase only in the proximity of small cells. mmWave systems are highly attenuated in the air, so human exposure will be lower by those antenna systems.

(d) **Offloading**: Legacy systems offload their traffic to 5G. As the legacy antennas emit wide beams, human exposure is expected to decrease from those systems.

(e) **3G shutdown**: RF exposure from 3G is removed.

(f) **Mobile Edge Computing (MEC):** The concept behind MEC is to move the cloud resources closer to the end users, by exploiting computing capabilities that are installed at the base stations. By managing the content stored in the MEC platforms, the operator improves the quality of services provided to the users that make use of this feature. As a result, a possible decrease of data transferred in the air, and consequently of EMF exposure is expected.

(g) **Device-to-Device communication (D2D):** This feature enables the user devices to communicate between each other, decreasing the data exchanged between the mobile base station and the user. So, the base station emits at lower power or for less time (duration).

(h) **Smart energy features** in use (Deep Dormancy, sleep modes, intelligent carrier deactivation): 5G technology and new operating systems give to the network the capability to self-optimize its activity to save energy where less traffic (less users) is recorded (for example at night hours). This self-optimization (Self-Organizing-Systems, SON) permits the network to shut down resources, thus, to emit in lower power. As expected, human RF exposure may be decreased (especially during the night hours).

(i) **IoT (Internet of Things):** Current specifications impose very low values of maximum transmitted power by each IoT terminal (lower than smartphones); Exposure from IoT devices will be below the ICNIRP’s limit; The distance and obstacles between the user and the IoT device force the exposure to negligible values (due to EMF attenuation). See also Chapter 5.

4.4.4 5G Exposure Assessment - International Surveys

In this section, a few RF exposure surveys are presented carried out by national regulatory bodies and labs. The purpose of these RF assessments is to evaluate the 5G exposure from the new antennas / networks in comparison with legacy networks (2G, 3G, 4G). Moreover, the surveys try to assess the new safety distances and the compliance with the ICNIRP's safety limits.

OFCOM is the regulator for the communications services in the UK (Office of Communications). In their technical report "Electromagnetic Field (EMF) measurements near 5G mobile phone base stations", with publication (updated) date 17 April 2020 [80], RF measurements results are presented from 10 UK cities (22 locations). The SRM-3006 analyzer with the electric field probe operates in the frequency range from 420 MHz to 6 GHz. This range covers all mobile services (2,3,4,5G). Big cities with considerable mobile traffic such as London, Manchester, Liverpool have been selected. The methodology standard selected was IEC 62232:2017 [79]. According to the results: "*In all cases, the measured EMF levels from mobile phone base stations are at small fractions of the levels identified in the ICNIRP Guidelines, the highest level recorded being approximately 1.5% of the relevant level. 5G currently contributes a small amount to the EMF levels measured at each location. At all locations, the largest contribution to the measured levels comes from previous generations of mobile technology (2G, 3G, 4G). The highest level observed in the band used for 5G was just 0.039% of the relevant level*". OFCOM continues to issue updated reports. In the last one (1/3/2021), the RF exposure (5G and total) remains at the same low levels.

ANFR (Agence Nationale des Frequences): France regulator is running a vast project on measuring the 5G exposure in France. The results are compared with the relevant values before the 5G roll out. Thus, an evaluation is performed on the possible exposure increase due to the new technology and the compliance with the ICNIRP's safety limits. The most updated report was issued in 2021 [81]. According to this:

154 sites operate in 700 MHz band. 135 sites in 2100 MHz, and 1360 sites in the C-band (3500 MHz, or 3490 to 3800 MHz). Of the total of 1649 sites, 85% are located at urban areas, and 15% in rural environment.

700 MHz results (in 143 out of 154 sites, 11 sites have no "after" measurements)

Before 5G: The median value is 0.16 V/m (700 MHz contribution) and 0.46 V/m (broadband value). Max value is 2.09 V/m (for 700 MHz band) and 3.40 V/m (broadband value).

After 5G: The median value is 0.19 V/m (700 MHz contribution) and 0.51 V/m (broadband value). Max value is 3.14 V/m (for 700 MHz band) and 4.50 V/m (broadband value).

Comment: The results show that 5G roll out in the 700 MHz band did not change the distribution of levels in this band.

2100 MHz results (in 1359 out of 1360 sites used for broadband values, 111 for the frequency of 3500 MHz)

Before 5G: The median value is 0 V/m (2100 MHz contribution) and 1.00 V/m (broadband value). Max value 0.28 V/m (for 2100 MHz band) and 6.19 V/m (broadband value).

After 5G: The median value is 0.09 V/m (2100 MHz contribution) and 1.01 V/m (broadband value). Max value is 1.25 V/m (for 2100 MHz band) and 5.41 V/m (broadband value).

Comment: The results show that 5G roll out in the 2100 MHz band did not change the distribution of levels in this band.

3500 MHz results (in 112 out if 135 sites, 33 sites have no "after" measurements)

Before 5G: The median value is 0.07 V/m (3500 MHz contribution) and 1.16 V/m (broadband value). Max value 2.1 V/m (for 3500 MHz band) and 4.98 V/m (broadband value).

After 5G: The median value is 0.33 V/m (3500 MHz contribution) and 1.18 V/m (broadband value). Max value is 2.58 V/m (for 3500 MHz band) and 4.33 V/m (broadband value). Comment: The results show that 5G roll out in the 3500 MHz band did not change the exposure levels before the C-band activation.

C-band exposure with data downloading scenario (1 GB)

It is of great interest to show the difference (if any) when the C-Band measurement is performed with 5G data download condition. In that case, high traffic occurs, and the power transmitted theoretically is increased. The traffic generated consists of 1 GB of data. 370 sites were considered.

Before download: The median is 0.99 V/m. The average is 1.21 V/m.

After download: The median is 1.13 V/m. The average is 1.34 V/m.

Thus, a 14% increase in the average value is calculated. According to the author [81]: *"One can therefore consider that an increase in 5G traffic in line with the exposure indicator introduced by the ANFR should lead to an increase of around 20 % in the overall exposure level".*

4.4.5 5G Exposure Assessment – Study on the Beamforming Effect

Based on theory and the new beamforming technique of the 5G antennas, we performed 5G measurements in a C-band base station at Maroussi, Athens. Chiaraviglio et al., 2021 [82], concluded that the pencil beamforming allows reducing the exposure over the deployment spots (user equipment, UE). The reduction is higher for those spots in proximity to the radiating 5G BS (gNodeB). See Fig. 4.16. The Medical Physics Lab performed RF exposure level measurements with a spectrum analyzer SRM 3006 and an electric field probe covering the range from 420 to 6000 MHz. It is a 3-axis antenna (type 3502/01) manufactured by Safety Test Solutions GmbH, Pfullingen, Germany, with a dynamic range of 0.14 mV/m to 160 V/m. The testing 5G BS operates at the C-band (3600 to 3700 MHz). According to our protocol, the 6-min average, and the max value of the electric field (E) was recorded in the following scenarios: a) "Mobile User": In the directed beam, a user equipment (UE) downloading YouTube traffic of 4K resolution was used to generate traffic) at 20m distance from the BS.

b) “Non-mobile User”: E-field is measured outside the beam. The UE remained active downloading, while the SRM moved 1m, 2m, and 3m left and right from the UE. The purpose was to evaluate the decrease of the electric field strength outside the directed beam supposing that a non-mobile user stands close to an active user. In the following charts, we see the exposure levels outside the beam that is directed to the active user. Note that L1 = 1m left, R1 = 1m right, etc.

We concluded that outside the main beam, the reduction of the average E-field is from 68 to 90% compared to the main beam. The highest reduction seems to appear at 2m from the active user (Fig. 4.17)

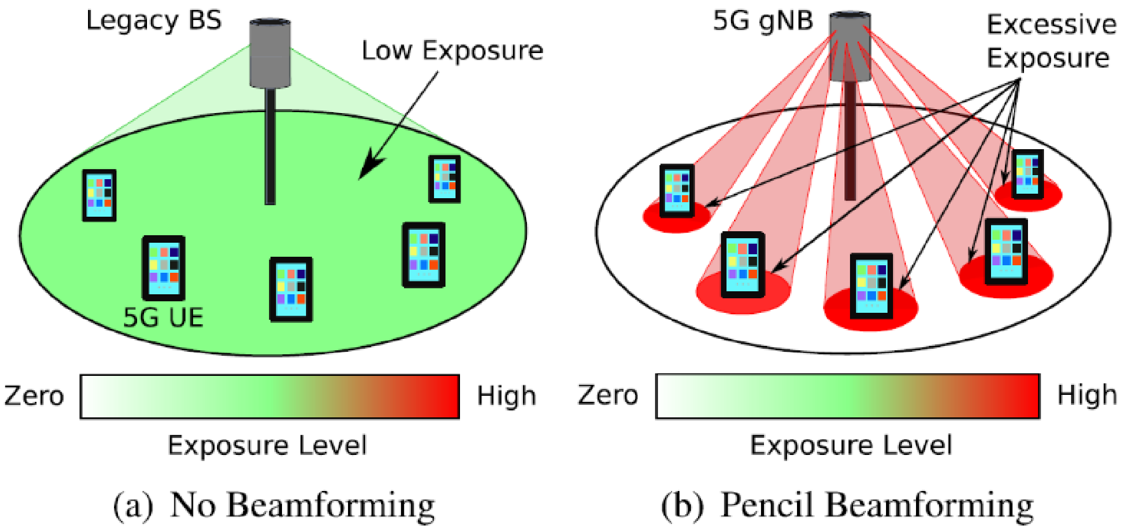

Figure 4.16. Chiaraviglio et al., 2021, provides a perception of beamforming technique w.r.t.the exposure levels around the devices served by the 5G BS.

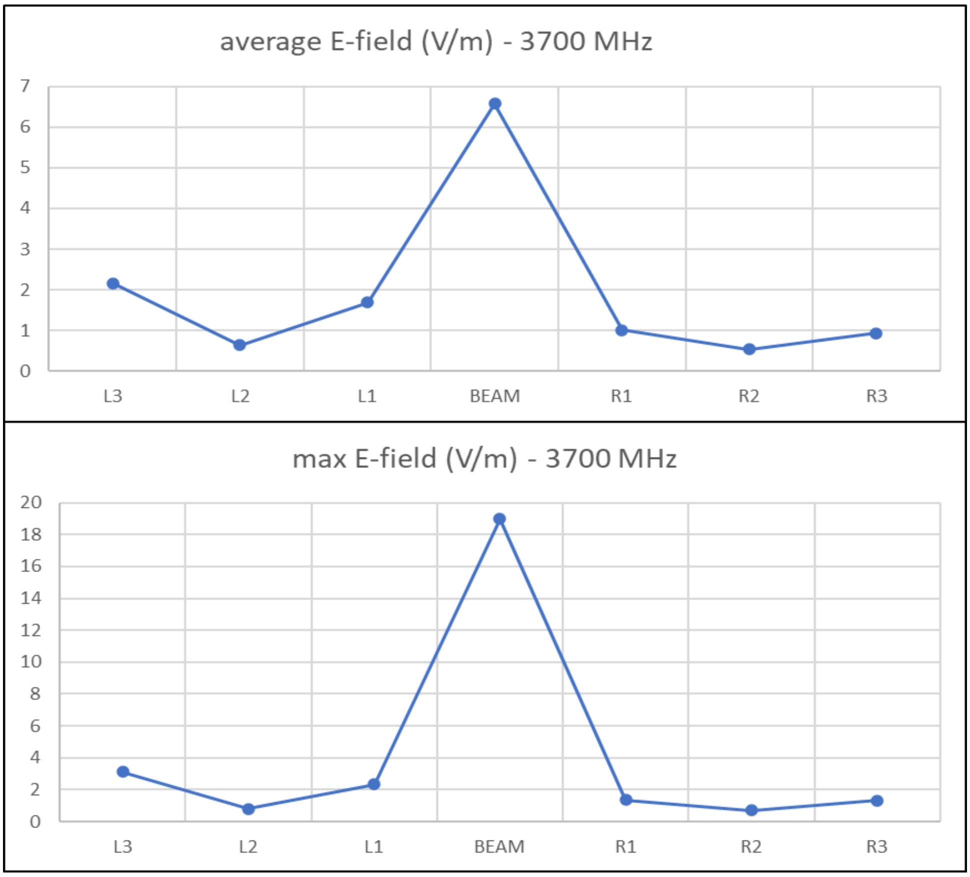

Figure 4.17. Exposure levels in C-band outside the main beam.

The uncertainty budget at that frequency band is presented in the following Table 4.1:

Table 4.1. Uncertainty budget for SRM 3006 and electric probe for 3600 MHz.

Components of Uncertainty U	**3600-3700 MHz**
Isotropy	12.05 %
Frequency Calibration (Frequency response)	25.15 %
Amplitude calibration (Level measurement accuracy)	10.12 %
Temperature Uncertainty	13.5 %
Body Influence (@2m)	18.85 %
Combined standard uncertainty	19.06 %
Expanded uncertainty (k=1,96 with 95% confident level)	**42.65 %**

4.5 Conclusion

The new 5G technology is going to exploit higher spectrum bands in the region of microwaves and millimeter waves. The spectrum in those areas provides users with high data transfer speeds and low latency. This gives rise to new services/applications such as IoT, virtual and augmented reality, remote health care (remote surgery), self-driving cars, self-organizing networks, smart homes, smart cities, and energy saving. The use of mmWave antennas will drive to denser networks in the future. In this Ph.D. work, we reviewed measurements up to 6 GHz (thus including the current 5G spectrum) from international bodies, confirming that the current levels of exposure have not changed compared to the legacy technologies. Moreover, we carried out narrowband measurements at 3.5 GHz, at the real field, evaluating the beamforming capability of the new 5G active antennas. Beamforming permits the emitted RF field to get directed to the user allowing a considerable decrease of the exposure levels outside the directed beam. As a result, the exposure from 5G networks is estimated to remain well below the ICNIRP 2020 safety limits. IoT study is presented in the next Chapter 5.

Chapter 5: New Wireless Technnologies – IoT

5.1 What is the Internet of Things (IoT)

When we refer to the Internet of Things (IoT), we mean the wireless communication between machine-to-machine (M2M) using 4G or 5G spectrum, and the wearable devices. There is significant interest in these services not only from people and their households but also from factories, organizations, and municipalities. The IoT controls multiple machines, devices and appliances including everyday objects such as smartphones, tablets and other consumer electronics and machines such as vehicles, equipped with IoT connectivity that allows them to send and receive data. M2M communication requires limited direct human intervention. A wide variety of antennas, monitors, and sensors are used to collect, transmit, and receive data. Smart wireless home applications (smart homes), services in healthcare, agriculture, and water / electricity distribution exploit the IoT capabilities. IoT devices operate at low powers with battery life of up to 10 years in some applications. This is possible because they will only transmit small amounts of information, using very low power and the transmissions will not be continuous. The transmission interval and the amount of data will depend on the application. RF fields are used in the M2M communication in different frequency bands according to the specification of the devices and the kind of communication they intend to establish. The data rate and the latency required are the two major factors to determine the technology that is to be used (4G or 5G). 5G with large bandwidths and minor latency is used in very demanding applications (such as gaming, virtual or augmented reality, remote surgery, self-driving cars etc.). In the following Figure 5.1, these 2 factors (latency – delay, and data transmission rate - throughput) is presented for different applications / services.

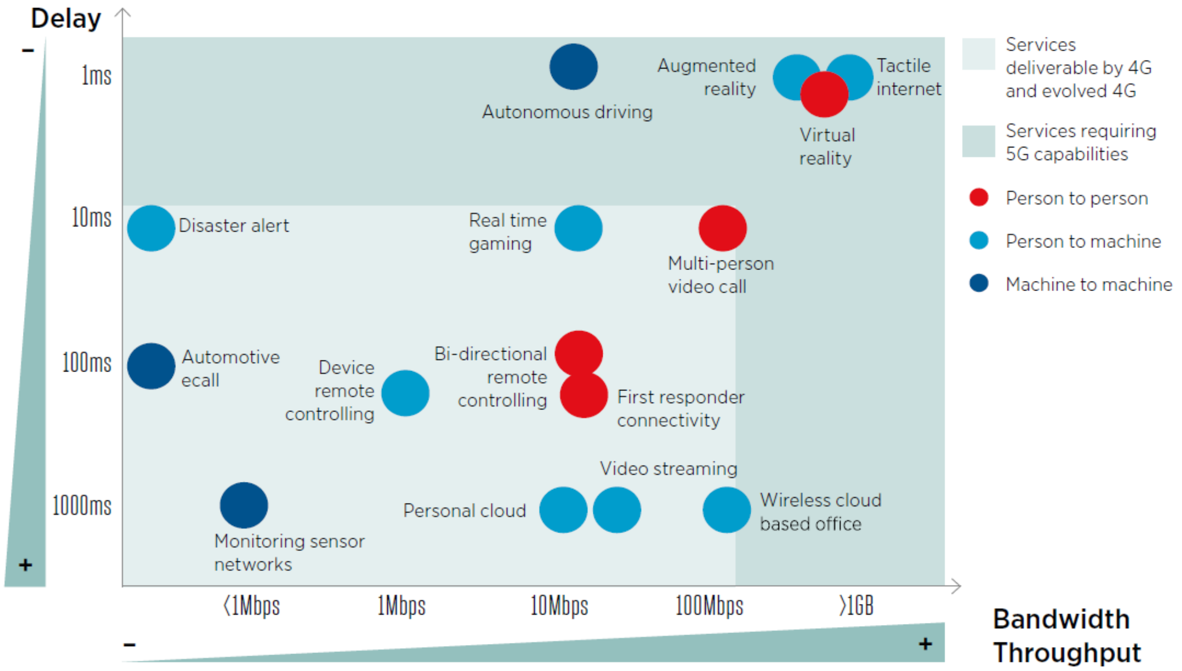

Figure 5.1. Services in 5G according to their requirements in delay and throughput. Source: GSMA, 2019 [83].

Applications using IoT technology

Within ETSI (European Telecommunications Standards Institute) various applications of IoT/M2M technology are supported:

- Smart appliances (smart homes, buildings, offices)
- Smart grids and meters. A Smart Grid is an electricity network that ensures economically efficient and sustainable power system with low losses and high levels of quality and security of supply and safety. A Smart Meter is an electronic device that records consumption of electricity, gas or water and communicates that information for monitoring and billing. Smart meters send meter readings to the utility company automatically. They also come with in-home displays, which give users real-time feedback on their energy or water usage and what it costs.
- Smart cities – Urban crowdy places with new demands on key services and infrastructure such as transport, energy, health care, water, and waste management. Energy efficiency is

the top target in every municipality nowadays.

- Smart Energy, Smart Environment, Smart Building, Smart Industry and Manufacturing, Smart Agri-Food, eHealth and Ageing-Well, Wearables, Smart Water, Smart Lift, and Smart Escalators
- eHealth (Telemedicine and the Internet Clinic, Medical implants, Body Area Networks, Pandemic protection, contact tracing)
- Intelligent Transport Systems – including telematics and all types of communications in vehicles, between vehicles and between vehicles and fixed locations. We also address the use of Information and Communications Technologies for rail, water, and air transport, including navigation systems.
- Wireless Industrial Automation – standards for radio equipment to be used in factories.

Billions of IoT are installed. In detail, 16.7 billion of IoT devices are connected (May 2023 data) according to IoT Analytics (https://iot-analytics.com/number-connected-iot-devices/). IoT Analytics is a leading global provider of market insights and strategic business intelligence for the IoT, AI, Cloud, Edge, and Industry 4.0.

5.2 Power and Frequency Used in IoT Devices

IoT devices operate now at frequencies above 30 MHz and below 6 GHz [83]. In the near future, higher band will be used (in the mmWave region) to achieve higher data rates and lower latency (minimum 1 msec). The operating power is very low (~ 0.15 mW) and the battery life of up to 10 years. A small amount of data and information is transmitted, and the transmission is not continuous. The duty cycle (DC) of operation is up to 10% (duty cycle = percentage of transmitting period to the average measurement period) [83]. Wearable devices operating above 30 MHz and below 6 GHz are covered by existing testing standards for wireless devices. Concerning future devices using higher frequencies, they will be covered by the forthcoming

5G standards that are under development. The radio transmitters in wearable devices generally operate at very low power to conserve battery life and often use familiar technologies such as Wi-Fi and Bluetooth.

5.3 EMF Exposure and Possible Health Effects from IoT Operation

Four factors affect the EMF exposure levels expected from IoT operations according to Aerts et al., 2019 [84]:

(a) The output power of the device (for example a smart meter).

(b) The frequency used for the signal emission.

(c) The distance from the device.

(d) The DC of operation (the proportion of time the device actually transmits a signal).

In [84] study, 10 residential environments were considered, with electricity, gas, and water smart meters connected. In this study, the EMF exposure levels were studied to assess the IoT contribution to the total field. The DC of most devices was very low. For example, a gas and a water meter operate with a DC of 0.002%, while the electricity meter operates at a DC of 1.05%. A thermostat meter exhibits DC of 0.02%. A temperature sensor has a DC of 23.76% and a Wi-Fi cable modem 15.80%. The last two are highest DCs met in residences. The electric field was measured at 0.2m from the device. The results are presented in Table 5.1.

Table 5.1. Average exposure levels in 10 residential environments from IoT and mobile communication sources at 0.2m distance [84].

Device	**Operating Frequency (MHz)**	**DC_{6min} (%)**	**Emax (V/m)**	**Limit ratio (compared to ICNIRP's limit)**
Gas meter	869	0.002	0.911	$4.6x10^{-9}$

Electricity meter	2.462	0.08	6.967	$11x10^{-5}$
Electricity meter	902-903	1.05	14.859	$1.3x10^{-3}$
RF motion sensor	2450	100	1.428	$5.4x10^{-4}$
Thermostat meter	868	0.02	2.627	$6.3x10^{-7}$
Temperature sensor	868	23.76	2.008	$5.9x10^{-4}$
WiFi modem	2.412	3.30	10.941	$1.0x10^{-3}$
WiFi printer	2.437	0.04	3.594	$4.8x10^{-7}$
DECT phone	1884	N/A	0.135	$1.8x10^{-4}$
Baby monitor (baby unit)	870	73.4	5.420	$1.3x10^{-2}$
Baby monitor (parent unit)	868	2.92	5.132	$4.7x10^{-4}$
Wireless mouse	2405-2474	100	4.045	$4.3x10^{-3}$
Smart toothbrush	865-868	33.63	4.820	$4.8x10^{-3}$
Mobile phone Uplink signal at 0.5m – GSM	900	12.5 (due to its TDMA	11	<0.1 (highest recorded)
Mobile phone Uplink signal at 0.5m – LTE	1800	100	2	0.01
(Worst case out of 10 residences) Outdoor RF base stations continuous emissions (FM, TV, Mobile, WiFi, etc) inside the residence	30 MHz to 3000 MHz	100	0.523	$1.3x10^{-4}$

It is obvious that IoT meters exhibit very low exposure keeping their emission levels thousands of times below the ICNIRP's levels for the general public. Their low operating power and the negligible (most of the time) DC, contribute to the low exposure. In the worst-case scenario, the exposure from outside RF sources (mainly FM, TV, and mobile antennas) was ~7600 times below the ICNIP limit. Considering the inside home sources, a Wi-Fi modem exposure at 0.2 m distance was 1000 times below, and an electricity smart meter 969 times below limit. Mobile phones (uplink) are the highest exposure when in use but below the adopted limits. According to the results of the study *"wireless access points (due to their usual deployment in highly frequented rooms combined with a DC of several percent), mobile phones, and other personal communication devices (e.g., DECT cordless phones, walkie-talkies; due to their typically high emissions and use close to the body) will probably continue to represent the bulk of the residential exposure to RF-EMF in the smart home".* A smart toothbrush exhibits high exposure in comparison to other devices due to its high DC and its close proximity to the body when in use. Considering that IoT devices are deployed away from human activity (in this study the 20cm distance seems to be very low and not met in real conditions), we conclude that their contribution to the human daily exposure is negligible.

5.4 IoT RF Measurements (Med. Physics Lab / University of Thessaly)

During this Ph.D. work, we performed RF exposure measurements at Trikala smart city, using an SRM 3006 spectrum analyzer (manufactured by Narda Safety Test Solutions, Pfullingen, Germany). The detection range of the main unit is 9 kHz to 6 GHz, while the electric field probe (type 3501/03) covers the range from 27 to 3000 MHz, with a dynamic measurement range from 0.2 mV/m to 200 V/m. This device allows the engineer to measure the electric field strength (V/m) either as a broadband value and in specific narrow bands (frequency selective measurements). The frequency selective measurements include 54 bands (according to the Greek spectrum allocation). The uncertainty calculation of the spectrum analyzer is presented in [52] paper. The expanded uncertainty was calculated at 3.66 dB (Type A and Type B included) for a 95% confidence interval (k = 1.96). RF measurements exhibited an uncertainty value of 52.41%.

Eight points of interest were selected focusing on IoT installation as well as external Wi-Fi antennas in the city. All IoT devices were located outdoors (streets, light masts, squares, etc.). In the following Table 5.2, we present the results in terms of electric field strength (broadband measurement), power density (derived from the broadband electric field), total exposure ratio ER (derived from the selective electric field measurements of the 54 bands, as the sum of the ratios of each frequency band power density to its relevant limit), and the times below the limit of the total exposure ratio. The total ER should be lower than 1.

Table 5.2. IoT RF Exposure levels in Trikala.

Point of measurement	**Point**	**Electric field strength (V/m)**	**Power Density (W/m^2)**	**Exposure Ratio (comparison with the ICNIRP limit)**	**Times below the ICNIRP limit**
1	Smart City office	0,364	0,00035	0,00011	8822
2	Wi-Fi	0,814	0,00175	0,00035	2838
3	Wi-Fi	1,224	0,00397	0,00073	1369
4	IoT Smart traffic light	0,298	0,00024	0,0001	10449
5	**IoT – Smart City lights**	**0,787**	**0,00164**	**0,0005**	**1990**
6	IoT - Smart Parking	0,512	0,00069	0,00026	3910

7	**IoT - Smart Parking**	**1,273**	**0,0043**	**0,0008**	**1251**
8	IoT - Gateway - Smart Parking	0,610	0,00099	0,00034	2931

An analysis of the different RF sources contribution to the total field is presented for two highest ER values: No 7 (Smart parking) and No 5 (Smart lights).

- **Smart Parking:** 52% of the total field exposure comes from UMTS mobile downlink signal (mobile base station operating at 2100 MHz band). IoT emission is included in "others" category, that contributes with less than 2% to the total human exposure. Measurement was performed at 20cm distance from the parking sensor (see Fig. 5.2 and Fig.5.3)

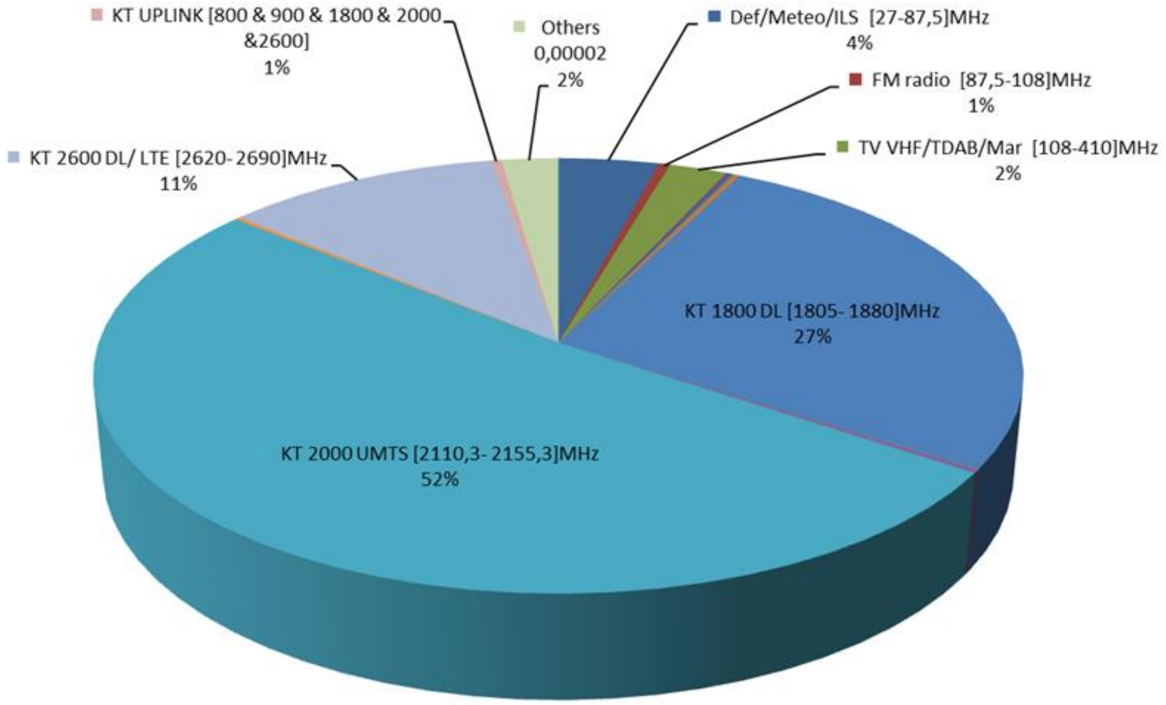

Figure 5.2. Analysis of the RF source contribution the total field at the smart parking point (above the sensor at 20cm distance)

Figure 5.3. Location of measurement. 20cm distance from the smart parking sensor.

- **Smart City lights:** 45% of the total field exposure comes from GSM mobile downlink signal (mobile base station operating at 900 MHz band). IoT emission is included in “others” category, that contributes less than 4% to the total human exposure. Measurement was performed at 20cm distance from the light sensor (see Fig. 5.4).

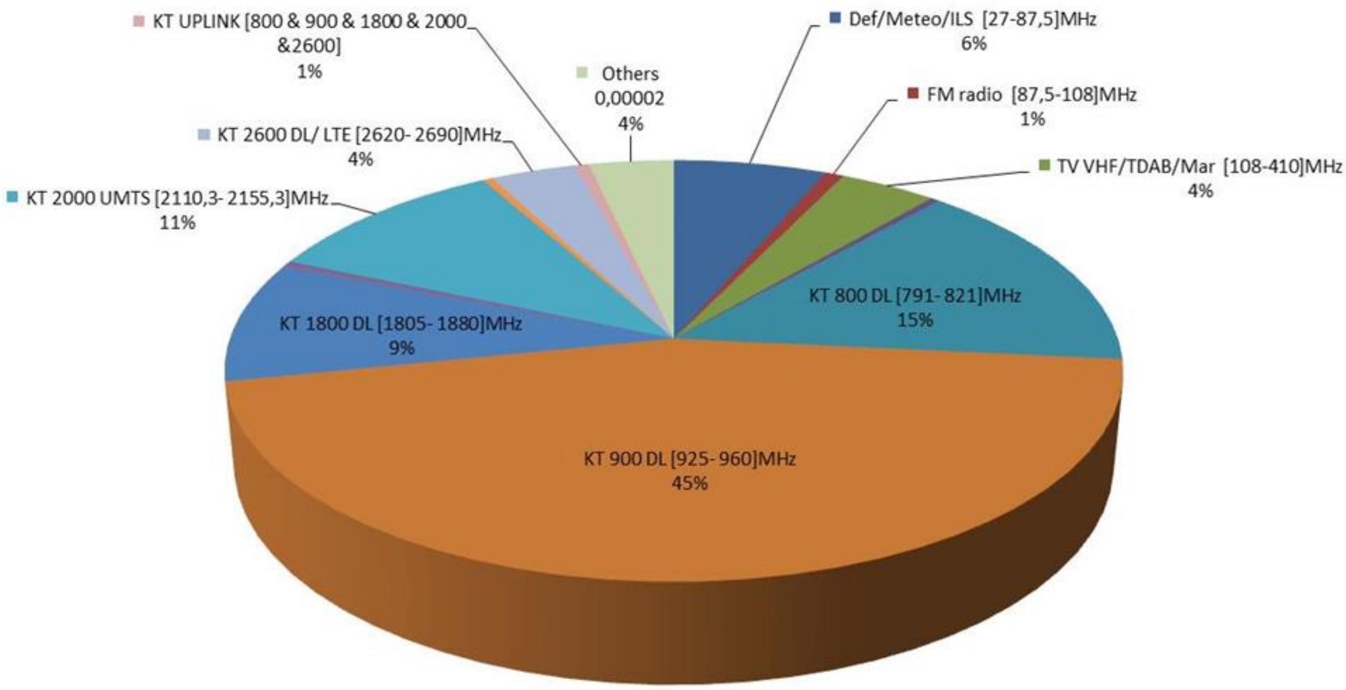

Figure 5.4. Analysis of the RF source contribution the total field at the smart parking point (below the sensor at 20cm distance).

5.5 Conclusion

As a conclusion, based on the current Ph.D.'s results and on other similar studies, the IoT devices emit in low power without changing considerably the total human exposure to RF EMFs. Existing technology covers the spectrum area from 30 MHz to 6 GHz. Future 5G IoTs will be operating at frequencies in mmWave bands, where the impact is superficial on the skin tissue. Based also on the fact that the distance from the human activity is considerable, and the duty cycle small, there is no evidence that this technology could impact human health or exceed the existing safety limits.

Chapter 6: Health and Biological Effects from 5G networks (review)

6.1 International Organizations Reviews on 5G

SCHEER (Scientific Committee on Health, Environmental and Emerging Risks): In the final opinion issued in April 2023 [29], SCHEER refers to the 5G human exposure: "*Smart meters and sensor networks (the Internet of Things, IoT) are becoming increasingly popular in all environments. Measurements of the RF EMF emitted from such devices in the residential environment have shown that residential levels of RF EMF exposure are low. Some residential devices can significantly increase the exposure if their duty cycles are high enough (>10%), especially when held or used close to the body. Individual smart meters, on the other hand, contribute little in general, despite emissions of up to 20 V/m at 50 cm, due to their low duty cycles (maximum 1%) and locations. So, in addition to the continuous exposure to environmental EMF, wireless access points (due to frequent use), mobile phones and other personal communication devices (due to their use close to the body) continue to represent the bulk of the RF EMF exposure in the smart home.*

The fifth generation (5G) of broadband cellular networks technology is a key enabling technology for the proliferation of the IoT. It uses devices within frequency range 1 (FR1) (< 6 GHz) and frequency range 2 (FR2) (24 – 54 GHz), that is a range of higher frequencies than those used in 4G (fourth generation) networks. The result is that some 5G signals do not travel large distances (over a few hundred meters), unlike 4G or lower frequency 5G signals (sub 6 GHz). The use of the higher frequency band (FR2) requires positioning 5G base stations every few hundred meters in dense urban areas, where resources such as power and data backhaul, links are available.

Millimeter waves are very weak in their ability to connect two devices, which is why 5G needs *something called 'small cells' to give full, uninterrupted coverage. Small cells are essentially miniature cell towers that would be placed 250 meters apart throughout cities and other areas needing coverage. The small cells are necessary as emissions (or signals) at this higher frequency/shorter wavelength have more difficulty passing through solid objects and are even easily intercepted by rain. The small cells could be placed on anything from trees to streetlights to the sides of businesses and homes to maximize connection and limit 'dead zones' (areas where connections are lost).*

Simulations on the deployment of 5G networks have shown that the exposure of the population could increase for the period of time they work in conjunction with previous generation networks but still remain well below the reference levels of the Council Recommendation for the NR FR1 band".

HCN (Health Council of the Netherlands): In this report (No. 2020/16e, The Hague, September 2, 2020) the Council's Standing Committee on Electromagnetic Fields advises on the scientific current state-of- knowledge on the health effects from the 5G exposure replying to the Dutch parliament's relevant request. According to the report, 5G frequency spectrum is not a new exposure. Legacy systems exploit very close bands to the 5G ones. For example, 4G uses 800 MHz, 1800 MHz or 2600 MHz, 3G used 2100 MHz, Wi-Fi exploits 5.4 GHz and some other applications the 26 GHz band in the past. It has reviewed the possible association between exposure to radiofrequency electromagnetic fields on the one hand and the occurrence of diseases and conditions on the other. According to the committee, "*it cannot be excluded that the incidence of cancer, reduced male fertility, poor pregnancy outcomes and birth defects could be associated with exposure to radiofrequency electromagnetic fields. However, the committee deems the relation between exposure and these and other diseases or conditions neither proven nor probable*". The committee has also examined the association (if any) between RF exposure and the biological effects. It is probable that changes in electrical activity in the brain are associated with exposure, but it is not known whether that may lead to health effects / damage. For most other biological processes, it has neither been demonstrated nor is it probable that changes in them are associated with exposure RFs. Impact in the immune system and hormone levels, is not found. There has been almost no research into the effects of exposure to frequencies around 26 GHz. The Committee suggests that exposure field measurements should be carried out before and after the roll out of 5G to evaluate possible increase in human exposure. Implication on health for frequencies below 6 GHz seem not to exist, although the band of 26 GHz should be experimentally and epidemiologically monitored. Finally, ICNIPR's updated guidelines should be adopted.

ICNIRP 2020 conclusion [3]: *"The only substantiated adverse health effects caused by exposure to radiofrequency EMFs are nerve stimulation, changes in the permeability of cell membranes, and effects due to temperature elevation. There is no evidence of adverse health effects at exposure levels below the restriction levels in the ICNIRP (1998) guidelines and no evidence of an interaction mechanism that would predict that adverse health effects could occur due to radiofrequency EMF exposure below those restriction levels".*

6.2 Health Effects Below 6 GHz

Frequencies below 6 GHz have already been used in wireless communications for the purposes of 2G, 3G, and 4G. WHO and ICNIRP have already included these frequencies in their safety guidelines. In chapter 1.5.3 biological and health effects are presented for RF frequencies in general based on the latest reviews by ICNIRP and SCHEER. In this paragraph we analyse some of the most important animal and population-based studies.

6.2.1 Animal Studies

The National Toxicology Program (NTP) and Ramazzini Institute study will be included in our review. 5G is operations in three areas: (a) below 1 GHZ at 700 GHz, (b) below 6 GHz at 3500 GHz, and (c) in the mmWave band above 6 GHz at 25 to 28 GHz in the near future and above 28 GHz. In the following table 6.1, we summarize test conditions met in the two experiments and how these are comparable to 5G networks emissions.

Table 6.1. Test conditions in NTP and Ramazzini studies.

Study	**Population**	**Frequency**	**Power**	**Duration**
NTP (2018a)	rats	900MHz (rats)	SARs up to 6 W/ kg (above limits) / Max 3800 Watts (5G macro-BS 200 W and 5G User equipment 0.2 W)	2 years (exposure several hrs. per day)
NTP (2018b)	mice	1900 MHz	SARs up to10 W/ kg (above limits)	2 years (exposure several hrs. per day)
Ramazzini	200 male and 200 female rats	1835 MHz	SARs up to 0.1 W/kg (slightly exceed the 0.08 W/kg of ICNIRP limit) / max 100 Watts	19 hrs. exposure per day

NTP Results

(a) Rats: Clear evidence of carcinogenic activity in Sprague-Dawley male rats due to malignant Schwannoma of the heart. This result not found in female rats.

(b) Mice: No clear evidence of tumors was found by considering male or female rats.

According to Chiaraviglio et. al., 2021 [85], the testing environment is very different from the real conditions met in the 5G networks exposure. First, the exposure duration from the mobile networks emissions and the users' equipment is not continuous (24/7) for humans. Second, the SAR and the power used in the experiment is much higher than the real exposure from the 5G antennas. In Ramazzini study, we meet lower exposure but still close or higher to the ICNIRP's limit. Consequently, it is not possible to claim that the health effects observed in these studies may appear in a real 5G deployment. Moreover, schwannoma of the heart is mainly reported in 6 W/kg absorption rate (much higher than the limit of 0.08 W/kg). Although NTP (2018a) reported significantly elevated rates of carcinogenic outcomes in male rats, their results are not consistent with the NTP (2018b) mouse or female rat results. NTP's finding is further complicated by important methodological limitations including the effect of the greater lifespans of the exposed rats on the statistical analyses, lack of blinding in the pathological analyses, and a failure to account sufficiently for chance in the statistical analyses. Finally, all the limitations preclude drawing conclusions on the carcinogenicity associated with RF emissions. ICNIRP also pointed out that such studies do not provide a consistent, reliable, and generalizable body of evidence. Further studies, tailored to address the limitations, are needed.

6.2.2 Population -based Studies

Population-based studies with considerable scientific interest are a) Interphone, b) Danish cohort, c) Million Women, d) Cefalo case-control.

Interphone Study [86], [87]: The INTERPHONE Study was conducted by IARC. The research took place in 13 countries from 2000 to 2012. The project goal was to study the impact of UE (user equipment) usage in people that developed severe diseases (i.e., glioma, meningioma, and acoustic neuroma), which may be connected to the usage of UE. The number of people involved in the study was more than 5000 patients with glioma or meningioma and 1000 patients with acoustic neuroma. A similar group of people, not affected by any of the tumors mentioned above, was also monitored. The adopted methodology involved several aspects such as personal interviews and validation studies collecting important data about UE usage (duration and frequency of the calls), as well as other relevant information (model, network operator, localization of the calls, user mobility and adoption of headsets or hands-free devices). The results of the study did not prove any connection between the usage of UE and the risk of developing glioma, meningioma, or acoustic neuroma. An increased risk of glioma for the highest RF exposure levels was observed. However, the presence of biases and errors in the data prevented a causal interpretation of such results. As a result, the importance of investigating possible long-term effects due to the heavy usage of UE was advocated by the team involved in the INTERPHONE project.

Danish Cohort Study [88], [89]: The goal of the Danish cohort study was to investigate the risks of developing tumors for Danish people having a subscription with a cellular operator against the remaining of the Danish population not having any subscription. The study was updated continuously throughout the years, the first period covering 1982 - 1995 and the latest one covering 1990 - 2007. The number of people taken under consideration is huge, almost 380000. The study did not show any link between the use of UE – even for more than 13 years - and the risk of developing tumors of the central nervous system. However, the principle adopted to distinguish between exposed people and non-exposed people is based only on their subscription with a mobile operator, without going into more in-depth details like the ones considered by the INTERPHONE project.

Million Women [90]: The methodology involved a postal questionnaire, which was completed by 1.3 million middle-aged women in the UK for different times during the years 1999-2009. The survey included specific questions to assess UE exposure, which was posed two times during the considered period. The results of the study showed that UE use was not associated with an increased incidence of glioma, meningioma, or tumors of the central nervous system. However, it is important to remark that the study is based on self-compiled questionnaires, and therefore bias and errors may have been (unintentionally) introduced by the participants.

Cefalo case-control study [91]: The CEFALO case-control study investigated the impact of UE exposure on young children and adolescents (with age 7-19) that developed brain tumors between 2004 and 2008 in Denmark, Sweden, Norway, and Switzerland countries. More than 350 patients were interviewed about UE usage (i.e., number of calls and call duration) and other relevant information, including, e.g., type of operator, number of subscriptions, starting and ending date of each subscription, adoption of hands-free devices, position of the UE during the usage, and (eventual) changes in the UE usage. The outcomes were then compared against a group of other adolescents/children, not affected by brain tumors, thus acting as control subjects. Results confirmed that children/adolescents regularly using UE were not statistically significantly more likely to have been diagnosed with brain tumors compared to subjects not using the UE. Also, no increased risk in developing brain tumors was observed for children/adolescents receiving the highest exposure. Eventually, the subscription duration was statistically significant with regard to the risk of developing a brain tumor for a small subset of the participants, whose activity information was retrieved from the logs of the mobile operators. However, as recognized by the authors of the CEFALO study, this outcome might be affected by multiple factors, including: i) a small cardinality of children/adolescent considered in the subset (only 35% of case-patients and only 34% of control subjects), ii) the fact that the UE might have been used by other people in the family and/or friends (i.e., not by the considered subject), iii) the possible presence of a reverse causality effect (i.e., children/adolescents affected by brain tumors use more frequently their UE compared to the ones not affected by the disease). Finally, the authors concluded that their work could not support a causal association between the use of UE and brain tumors.

6.3 Health Effects Above 6 GHz - mmWave radiation

Future 5G networks will also operate in higher bands called millimeter Wave bands as discussed in Chapter 4. A very informative review on possible health effects on that spectrum region is performed by Karipidis et. al., 2021 [92]. We will summarize the main points:

Effect of millimeter waves on genotoxicity

According to [92], "*Genotoxicity was mainly examined by using comet assays of exposed cells. This approach has consistently found no evidence of DNA damage in skin cells in well-designed studies. However, animal studies conducted by one research group reported DNA strand breaks and changes in enzymes that control the build-up of ROS, noting that these studies had low animal numbers (six animals exposed); these results have not been independently replicated. Studies have also investigated other indications of genotoxicity including chromosome aberrations, micro-nucleation, and spindle disturbances. The methods used to investigate these indicators have generally been rigorous; however, the studies have reported contradictory results. Two studies by a Russian research group have also reported indicators of DNA damage in bacteria, however, these results have not been verified by other investigators*".

Effect of millimeter waves on cell proliferation

Karipidis et al., 2021 [92], collects info from many studies based on bacterial cells. Growth rate of E. Coli were impacted but all these studies reported problems in dosimetry and statistics. Overall, the results from studies on cell proliferation of bacterial cells have been inconsistent with different research groups reporting conflicting results. There are also studies on the effects of mmWaves on tumor cells concluding possible anti-proliferative effect (reduction in the growth of a variety of tumor cells exposed). An Italian research group published a number of studies investigating proliferation effects on human melanoma cell lines with conflicting results. Inadequate dosimetry data should be considered.

Effect of millimeter waves on gene expression

According to [92], "*the studies on gene expression mainly examined two different indicators, expression of stress sensitive genes and chaperone proteins and the occurrence of a resonance effect in cells to explain DNA conformation state changes. Most studies reported no effect of* *low-level mmWaves on the expression of stress sensitive genes or chaperone proteins using a range of experimental methods to confirm these results; noting that these studies did not use blinding so experimental bias cannot be excluded from the results. A number of studies from a Russian research group reported a resonance effect of microwaves, which they propose can change the conformation state of chromosomal DNA complexes. Their results relied heavily on the AVTD method for testing changes in the DNA conformation state, however, the biological relevance of results obtained through the AVTD method has not been independently validated".*

Effects on Cell signaling and electrical activity

According to [92], "*Studies on cell signaling and electrical activity reported a range of different outcomes including increases or decreases in signal amplitude and changes in signal rhythm, with no consistent effect noting the lack of blinding in most of the studies. Further, temperature contributions could not be eliminated from the studies and in some cases thermal interactions by conventional heating were studied and found to differ from the mmWaves effects. The results from some studies were based on small sample sizes, some being confined to a single specimen, or by observed effects only occurring in a small number of the samples tested. Overall, the reported electrical activity effects could not be dismissed as being within normal variability. This is indicated by studies reporting the restoration of normal function within a short time during ongoing exposure. In this case there is no implication of an expected negative health outcome*".

Effects on Cell membrane or other effects

Although many membrane bioeffects are reported, they cannot be independently replicated. Limited number of studies have been carried out on other effects below the ICNIRP limits. Little or no consistent effects have been recorded. Only one in vivo study on cancer promotion did not find an effect although the study did not include sham controls. Effects on reproduction were contradictory. Moreover, the only study on human sperm concluded no effect. The studies on reproduction suffered from inadequate dosimetry and temperature control, and since sperm is sensitive to temperature, the effect of heating due to high RF energy deposition may have contributed to the studies showing an effect. A variety of bioeffects have been reported in experimental studies but the results could not independently be reproduced and confirmed by different laboratories. In meta-analysis, no dose-response relationship was established. Exposure and effect could not be combined. Most of the studies used frequencies above 40 GHz. Next 5G stage will exploit frequencies between 24-28 GHz. Focus on those bands is essential.

Effects on immune system

It is known that mmWave frequencies are used in therapy of several diseases in Eastern European countries and ex-Soviet Union. A list of mmWave applications includes therapy of gastrointestinal diseases, diabetes, coronary artery diseases, pulmonary diseases, psoriasis, and atopic dermatitis. Bone and wound healing are also involved. Pain relief is the most usual target of this therapy [93]. In cancer patients, mmWaves are used in combination with chemotherapy providing protection to the immune system from toxicity of chemotherapy. It has been reported by SCHEER [29] that mmWave therapy reduces tumor metastasis or the resistance to the chemotherapeutic drugs. As a result, there is no weight of evidence for any negative impact of these fields to the immune system.

Epidemiological Studies

Epidemiological studies (*31 epidemiological studies: 8 cohort, 13 case-control, 9 cross-sectional and 1 meta-analysis*) based on mmWaves exposure from radars that use frequency bands similar to that of 5G technology with exposure below the ICNIRP occupational limits, provided little evidence of an association with any adverse health effects including cancer at different sites, effects on reproduction, and other diseases. Studies that reported positive associations suffer from serious methodological weaknesses such as bias impact. The three large cohort studies of military personnel exposed to radar did not conclude an association of mmWave exposure and cancer or other diseases. The quality of the exposure assessment is poor in all studies available, and this is a serious scientific issue to overcome in the future. The exposure in most of the epidemiological studies was self-reported and based on the job-title, for RF fields above 6 GHz. Lifestyle factors and other occupational exposures add uncertainties in the results [92]. 5G technology now makes use of below 6 GHz spectrum. So, epidemiological studies from mobile phone users are not available.

According to Simko et al., 2019 [94]: *"Regarding health effects of mmWaves in the 6–100 GHz frequency range at power densities not exceeding the exposure guidelines the studies provide no clear evidence, due to contradictory information from the in vivo and in vitro investigations. Regarding the possibility of "non-thermal" effects, the available studies provide no clear explanation of any mode of action of observed effects. Regarding the quality of the presented studies, too few studies fulfill the minimal quality criteria to allow any further conclusions".*

As a result, neither experimental studies, nor epidemiological available studies, support an association between mmWaves exposure below ICNIRP's 1998 and 2020 guidelines (general public or occupational) and health effects.

6.4 Beyond 5G: Future networks and challenges on health protection

As discussed in this chapter 5G exploits microwave (3.5 GHz) and the mmWave spectrum area (above 30 GHz, in Greece there is already available spectrum at 27 GHz for the 3 operators). Adopting higher frequency bands in mobile communications, we end up with the following network characteristics:

- Larger bandwidths, thus better capacity conditions, and therefore higher data speeds rates.
- Smaller cells (microcells / picocells): The areas served are decreasing by increasing the frequency (as the attenuation increases). In most cases, the range of a microcell is less than two kilometers wide, whereas a micro-BS covers up to 35 km. A picocell, on the other hand, extends to 200 meters or less, and a femtocell range is few meters (10 meters). The smaller

the cell, the more BSs (antennas) are needed to cover the geographical area (denser networks).

- Dense networks lead to shorter human – antennas distances. This may raise a challenge of compliance with the limits. According to our knowledge and standards, micro and pico antennas operate at very low power (like the IoT devices) and their possibility to exceed the limit is negligible. Of course, the installation of a micro or pico antenna should not be reachable by the human body (not touchable).

According to 5GPP Whitepaper (2023) "Beyond 5G/6G EMF Considerations", 6G networks are expected to use even higher frequencies in the sub-Terahertz area (100-300 GHz). These very high frequencies, as discussed, can have only superficial skin tissue effect (mm penetration). Bibliography for these bands is limited. 6G will be based in a heterogeneous network (HetNet) with macro base stations and many pico cells that will improve indoor coverage providing too high speeds (see Fig. 6.1). Non-terrestrial networks (NTN, drones) will also be operating.

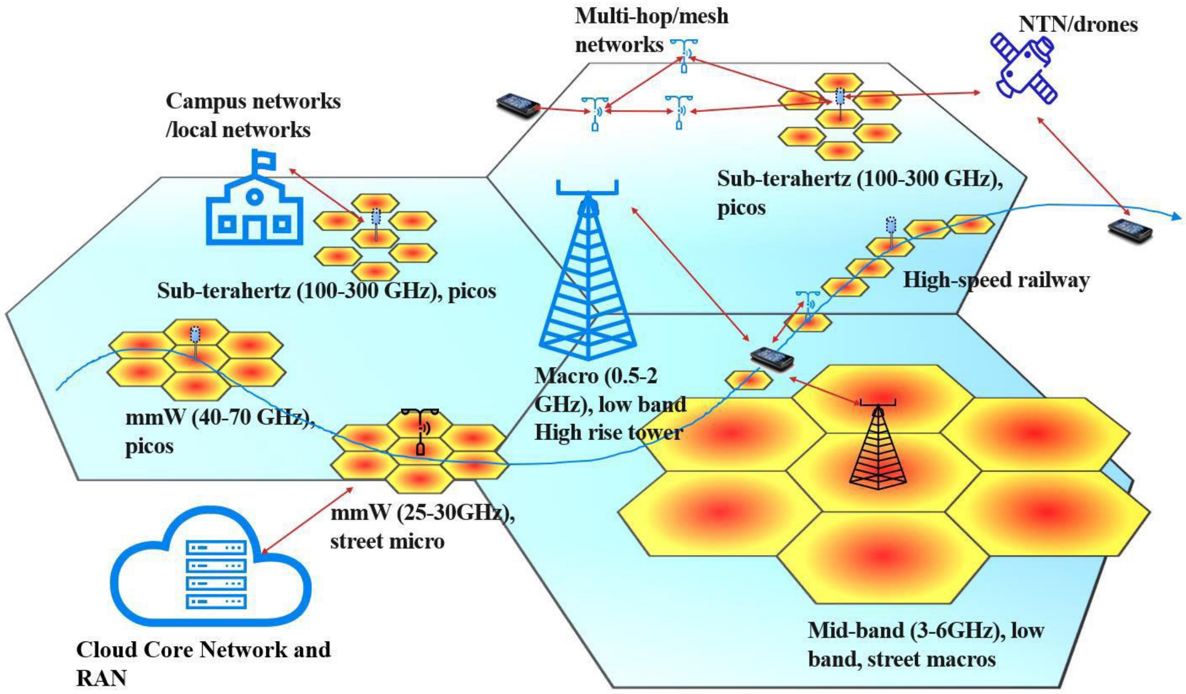

Figure 6.1. 6G – the network of networks. mmWave and Sub-THz bands in use. Source: 5GPP Whitepaper (2023)

New EMF protection challenges

The deployment of 5G mobile networks and the emergence of 6G mobile networks create new EMF challenges because of the introduction of new technologies, the use of new frequency bands (e.g., higher frequencies such as mmWave and sub-Terahertz) and the coexistence of several generations and operators in the same mobile site. In order to address these new challenges, we need an updated EMF framework including (according to RISE 6G, 2021 [95]):

- A clear definition of the new studies that need to be conducted, fine-tuned to the new 5G/6G technologies and characteristics.
- A well-defined set of EMF related Key Performance Indicators (KPIs) such as self-EMF exposure, Inter-EMF exposure, and energy efficiency.
- A well-defined set of EMF measurement and monitoring methodologies.

In addition, the radio frequency exposure guidelines and limits may need further consideration from ICNIRP and WHO.

Note: *The 5G Infrastructure Public Private Partnership (5G PPP) is a joint initiative between the European Commission and European ICT industry (ICT manufacturers, telecommunications operators, service providers, SMEs and researcher Institutions).*

PART THREE: DISCUSSION & CONCLUSIONS

Chapter 7: Discussion and Future Work

7.1 The Background. What was the need for a study?

Non-ionizing EMF radiation has become an important area of investigation in the last decades. The reason is the wide spread of wireless technologies with vast number of daily applications and services. Mobile communications evolution since 90's is incredible providing the users with a variety of capabilities except mobile calls and messages. W-Fi spots, local networks, smart devices, wearable devices, internet of things, machine-to-machine communication, artificial intelligence, virtual reality, augmented reality, autonomous driving, remote surgery, are some of the current and future application of the wireless technology. The last pandemic pointed out the necessity of remote activities such as education, banking, and medicine. Mobile networks played the most important role in keeping society connected and alive. But what could be the biological and health effects of spending more and more hours daily close to EMF multiple sources of multiple intensities? Are the RF exposure levels in our daily environment high? Are the safety limits capable of ensuring no health or biological effects? Is scientific research sufficient and up to date for the new 5G technology? What is the status of knowledge and where the scientific investigations should be focused on? All these questions are being addressed in this PhD thesis. EMF exposure levels measurements is the most reliable proposal to ensure human safety. There are three considerable difficulties with that venture. First, the enormous variations behind these measurements. The RF environment is dynamic. New sources are added every day, other sources are switched off. The number of concurrent users changes the field intensity. The electromagnetic fields are heterogenous, and the environment exhibits areas of hot spots (high levels of exposure) and areas of low-level fields (background levels). So, the choice of measurement points plays an important role in exposure assessment. Spatial and temporal diversity should be considered. The second issue to address is the uncertainty of these measurements. Laboratories should describe in detail the methodology and the materials used. A different setting on the measuring device could lead to a different result. Another factor that impacts the results and their evaluation is the safety limits adopted. Unfortunately, different limits are adopted world-wide. WHO and ICNIRP are the responsible organizations to provide guidelines based on the current scientific research, based on all the up-to-date bibliography including "positive" and "negative" articles. Nations should adopt these guidelines. But this is not a fact. Greece and other countries as well, based on political and not scientific reasons, prefer to adopt stricter limits. Not a health reason behind this, nor a proactive behavior. Adopting different limits, countries increase public concern, cautiousness towards the scientists, and the technophobic attitude.

7.2 How does this PhD thesis address the EMF concerns?

- In the frame of the National EMF research program (EDBM34), this Ph.D. work had the scope to measure (and then evaluate) both Low-Frequency (LF) and the Radiofrequency (RF) radiation levels in areas of sensitive land use in Greece. One thousand (1000) measurements were carried out in RF, and 247 measurements in ELFs. The big number of selected spots provided the scientific community with an accurate perception of the human exposure as the 80 % of the Greek population was covered (7 out of 13 regions, 78.89% of population included). Uncertainties were minimized. Different environments were selected (heavy urban and rest urban areas). Comparison of human exposure in these different environments was performed to clarify the role of the network density to the total exposure. Dense network means too low distances between EMF sources and human accessible areas. The visibility of an antenna system increases people's concern.
- ICNIRP updated its safety guidelines and limits (2020 issue). Before those guidelines there was a gap of 22 years without any update in terms of policy and regulation from the

responsible organizations even if IARC categorized EM fields (RF and ELF) as “2B”. This category is used for agents, mixtures, and exposure circumstances for which there is limited evidence of carcinogenicity in humans and less than sufficient evidence of carcinogenicity in experimental animals. It may also be used when there is inadequate evidence of carcinogenicity in humans but there is sufficient evidence of carcinogenicity in experimental animals. In some instances, an agent, mixture, or exposure circumstance for which there is inadequate evidence of carcinogenicity in humans but limited evidence of carcinogenicity in experimental animals together with supporting evidence from other relevant data may be placed in this group. This Ph.D. considered both the legacy (1998) and the current (2020) guidelines. We performed RF measurements following both guidelines. We also compared the results with the strictest Greek safety limits and confirmed that human exposure is well below the safety limits.

- During this Ph.D. thesis, 5G network were starting to be deployed in Greece in 700 MHz, 2100 MHz, and 3500 MHz. We didn’t have the chance to measure a mature 5G network with many subscribers active and a heavy traffic load. Moreover, during the National EMF research program and the 1000 RF measurements performed, the spectrum analyzer covered the area up to 3000 MHz. Based on this, we missed the 3.5 GHz emission even if the deployment of this network is immature even up to now. To overcome and address this weakness, we performed a few indicative measurements in areas with 3.5 GHz coverage the last 12 months of the Ph.D. work, using another detection probe that covers emissions up to 6 GHz. On top, to enhance our conclusion, we reviewed the most important international surveys in 5G performed by OFCOM in UK, and ANFR in France. Considering all this info, we managed to drive conclusions on the expected 5G exposures in Greece the forthcoming years.
- IoT and smart devices / meters are a part of our life and will be used more and more in the near future. In this thesis, we covered the issue, presenting RF exposure measurements in

the proximity of such installations. Based also on theoretical standards, we concluded on their safe usage.

- In the beginning of the thesis, a chapter with the latest biological and health effects reviews due to EMF exposure are presented. A dedicated chapter on 5G health impact is available since this technology differs in the concept from legacy technologies. The latest epidemiological and animal experimental studies were presented. Current scientific opinions and updated guidelines are included.

7.3 Discussing the results of the experimental part

This Ph.D. work provided conclusions of the human exposure to Low frequencies, Extremely Low frequencies (LF and ELF), and Radiofrequencies (RF) in urban and rural environment at areas of sensitive land use. The choice of sensitive areas (schools, hospitals, elderly homes, kindergartens etc.) was based on the strictest safety limits adopted in Greece for those places. Moreover, our intension was to address the public concern for people with special needs and care.

Discussion on the RF study: One thousand (1000) measurements were conducted in the frequency range between 27 MHz and 3000 MHz. Including all the existing technologies / services except the C-band (3500 MHz). Two (2) different environments were studied. Metropolitan areas (Athens and Thessaloniki), and Rest Urban - Rural areas (rest of Greece). Concerning Athens and Thessaloniki (624 spots), the mean electric field (E) strength was 0.41 V/m with a median of 0.34 V/m, while the maximum recorded exposure was the 0.129 % of the ICNIRP's 1998 (or 2020) limit. For the rest of Greece (376 spots), where no dense networks exist, the mean E field strength was 0.36 V/m with a median of 0.30 V/m, while the maximum recorded exposure was the 0.110 % of the ICNIRP's 1998 (or 2020) limit. Mobile Baste Stations (BSs) contributed 14.9 % to the total RF exposure, while TV and Radio broadcast emissions reached 36.2 %. People are aware of the need for antennas to communicate wirelessly. There is also a high penetration in mobile phone use and other devices. But, on the contrary, they feel unsecure when an antenna is close to their living area. In fact, they are afraid of dense networks. Around 63 % of the Greek population believe that base stations have an impact on their well-being and health [74]. The 73 % of Greeks admit that TV is the most important source of information on the issue. Our results proved (under a statistical comparison analysis) that the RF exposure is comparable between big towns (such as Athens) and rest urban areas (such as Larissa). Moreover, the study proved that mobile networks are not the main source of human exposure. TV and radio transmitters lead the rank of exposure sources. If we recall the absorption rate resonance diagram in humans, the peak of RF absorption is found at 80-85 MHz. Thus, humans absorb the maximum of energy at the Radio FM band. Absorption is decreasing with increasing frequency after the resonance point. Moreover, if we recall the derivation concept of limits, and that human exposure in Greece is found many times below them, we conclude that human well-being is ensured. Basic restrictions are set 50 times below the possible thermal effect (body temperature increase of 1 °C). Realistic daily exposures are thousands of times below the adopted threshold (highest recorded exposure in Athens / Thessaloniki at 0.129 % of the limit). We should note that non-thermal effects are not proved or supported based on the whole international bibliography. Our results are aligned with other important surveys world-wide.

5G is a completely new technology in terms of antennas' emissions. As discussed, 5G active antennas bring two (2) new technologies: MIMO and Beamforming. MIMO and massive MIMO provide very high users' throughput (data transfer rate) and capacity. Beamforming means that the antennas' beams are directed to the users, keeping the exposure focused and not spread in big lobes as in the legacy technologies. It is important to note that even at 1-2 m away from the user, the electric field is decreased more than 60% providing that the antenna is close to user (10-20m). Our indicative measurements did not support the same result in case the antenna is located far away from the user. For example, at 50 – 100 m distance, the field is becoming homogeneous. More measurements are needed in this direction to investigate in depth the beamforming impact on human exposure. Measurements should be performed at a 5G BS without interference from other users nearby (a testing environment is proposed in a Faraday cage (area shielded to block other electromagnetic fields to enter). If many users exist, the field will become almost homogeneous. 5G exposure consistent surveys are not yet performed in Greece (3500 MHz band is under roll out). In the forthcoming years, more 5G measurements should be carried out to highlight the increase or not of human exposure due to the addition of this technology. These measurements are better carried out in spots where past surveys were performed to achieve a clear comparison. In UK and France two major surveys are running under this concept. OFCOM and ANFR organizations investigate the possible increase of RF human exposure in the areas with 5G (C-band) coverage. OFCOM concludes that 5G contribution is low (under 1 % of the reference levels) to the total field. The total exposure of the highest recorded field is 1.6 % of the reference level So, even if there may be an increase of the total exposure compared with legacy technologies, these new RF levels are still low and comparable to the past ones. ANFR concluded the same. They recorded a small increase in RF levels. For example, before 5G in 3.5 GHz, the median electric field out of 112 sites, was 0.07 V/m. After the induction of 3.5 GHz, the median value reached 0.33 V/m. So, the two environments can be considered the same. ANFR, on the top, investigated the case of downloading traffic. When the user downloads data, the expected field in his location should be increased due to the directed beam from the antenna. In fact, ANFR recorded an increase of 14% when the user is downloading data in the C-band compared with the field level in pilot mode (without data transfer). Based on theoretical assumptions, they concluded that a 20 % increase could be expected in human 5G exposure when downloading data. Even with this expected increase considered, the total field strength cannot exceed the ICNIRP's reference levels. In Greece, similar measurements should be scheduled, to achieve a clear perception on the impact of the directed beams to the human exposure, as people use their mobile phones many hours per day.

As far as the **Internet of Things** and Machine-to-Machine communication concerns, the low power used, the emission for a small fraction of time (Duty Cycle around 10%), the considerable distance from the human body, and the mmWave frequency that will be used in 5G IoT devices, lead to the conclusion that there is no possibility for the human exposure to reach the existing reference levels.

Finally, it is important to focus the scientific investigations on mmWave fields. Fields above 6 GHz, and most probably above 30 GHz, will be used in special cases to improve capacity, provide excessive data speeds, decrease the latency, and enforce the use of future IoT applications. As the emissions of mmWave face a considerable attenuation even in the air, a dense network is expected to be used to provide an acceptable quality of service. The penetration of mmWaves (above 30 GHz) remains on the top layers of the skin under 0.16 cm in depth and impacting under 1 % of the total body. As the use of the highest bands were limited in the past to special cases (links, radars), the scientific community should follow up the possible health impacts (adverse, favorable, or lack of effects) based on the skin effects. Up to date, experimental and epidemiological available studies, do not support an association between mmWave exposure below ICNIRP's 1998 and 2020 guidelines (general public or occupational) and adverse health effects.

RF fields are used in medical treatment processes and therapy (thermal therapy, radiofrequency surgery and ablation). In thermal therapy, local temperature generated by the RF fields is increased. The tissue is heated at certain parts of the body to accept the therapeutic effect. In diathermy applications (13 MHz to 430 MHz), the depth of penetration is around 20 cm. Microwave therapy is performed at 2.45 GHz and it has a depth of penetration of a few centimeters, depending on the water content (thus conductivity) of the tissue. Powers of up to several hundred watts with partial body SAR values of 10 to 50 W/kg are applied in microwave therapy (above the Basic Restriction level).

Above the mmWave bands (> 300 GHz), we meet the Terahertz frequencies (THz). In fact, this band will be used in the future in industry, imagine techniques, and short-range communications. Its power will be low. Superficial tissues can only be affected due to very small penetration capability. The number of studies available is not big but it increases. In vivo studies indicate mainly beneficial effects on disorders of intravascular components of microcirculation in rats under immobilization stress, but do not address acute and chronic toxicity or carcinogenesis. In vitro studies on mammalian cells differ greatly with respect to irradiation conditions and endpoints under investigation. There are studies suggesting health effects of exposure, but these have not been replicated based on SCNIHR's 2015 opinion [9].

Discussion on the LF and ELF study: During the PhD thesis, a big survey on the Low frequencies human exposure took place. Three (3) different environments were selected to address all possible cases in our daily life: urban, suburban, and areas in proximity of power stations. The maximum values recorded are 2.09 μT for urban, 0.53 μT for suburban and 1.90 μT for power stations. Median values were 0.18 μT for urban, 0.11 μT for suburban, and 0.01 μT for power stations. Mood's analysis indicated that the three environments do not support any significant statistical difference. The maximum exposure levels of the 3 environments were compared with the ICNIRP 1998 (Greek approach) reference levels and the results were: 2.79% for urban, 1.59% for suburban and 2.70% for power stations of the reference levels. The results of this study were aligned and comparable with other similar studies of the international bibliography.

Lessons learnt from occupational exposure in the much more demanding working environment, have been incorporated in the ICNIRP guidelines and the Directive 2013/35/EU, and thus the current scientific EMF knowledge. Any alleged EMF health effect must be crosschecked against any hazardous agent that could contribute to the suspected outcomes. Social characteristics of the population that lives near power lines should be considered when assessing possible deterioration of their wellbeing. According to Amoon et. al., 2018 [96] *"there was no material association between childhood leukemia and distance to nearest overhead power line of any voltage. Among children living < 50 m from 200 + kV power lines, the adjusted odds ratio for childhood leukemia was 1.33 (95% CI: 0.92–1.93)"*.

According to the current knowledge, the average exposure of the public in European countries is too low, up to 0.1 μT. Approximately 0.5% of the population is exposed to levels above 0.2 μT derived from the power distribution installations (i.e., high-voltage power lines, lines of transport systems). Household electric devices consist of a major source of public exposure, but the duration of such exposure is extremely limited in most cases. High levels of magnetic fields are reported in the kitchen or close to transformers. In terms of cumulative exposure, approximately one third of the total exposure experienced by an individual can be attributed to the use of personal appliances. In conclusion, ELF levels in the European population are significantly below the ICNIRP's 2010 limits at 50 Hz (200 μT) and the 1998 limits (100 μT). Moreover, technological changes in Europe during the last years have led to the introduction of new LF sources. For example, LED lamps are being used instead of energy-saving lamps, electric cars, batteries from mobile phones, tablets, laptops. Ad-hoc measurements of electric and magnetic fields from responsible, trained personnel are needed to record daily general public exposures from new devices, contributing to epidemiological studies.

7.4 The overall conclusion of the PhD thesis

In this PhD thesis, we tried to assess the EMF human exposure in Greece, in different environmental conditions, different spectrum bands in the non-ionizing part, specifically in areas of sensitive land use. Focus was made in the RF part and in mobile communications. As the penetration of wireless applications is enormous, and the technology exhibits a huge evolution in the last decades (5G, IoT, smart cities, smart homes), the need to study both the exposure levels and the mechanism of possible health effects is of great importance. All our measurements, even in worst-case scenarios, were in compliance with the ICNIRP limits as they have been adopted by the Greek nation (Greece adopts stricter limits in RF and LF than ICNIRP). Moreover, the geographical variation of the measurement spots didn't play any role in the results. Urban or rural areas exhibited comparable EMF exposure levels. The network density seems to not impact the results. Special exposure cases, such as residential LF exposure due to electrical appliances, and RF exposure from smart devices / meters, were too low and could not pose any risk to the human health. The considerable evolution of wireless technologies is expected to increase the daily human exposure, but the levels are also expected to remain low and many times below the current safety limits. It is of great importance for the safety guidelines and limits to be harmonized across countries enhancing people's trust to the scientific community. ICNIRP's new safety guidelines are based on the current state of knowledge providing protection with large safety margins.

7.5 Future proposed work

During the period of this PhD thesis, the 5G networks were starting to be deployed. Even nowadays, the network at 3500 MHz (C-band) is not mature. mmWave bands are not used until now but the spectrum is available for the operators. This means that the roll out is limited to big towns and special cases. So, we didn't have the chance to perform comparison measurements between the exposure levels under the legacy technologies (2G, 3G, 4G) and the exposure with the 5G on the top. An interesting project in the forthcoming months is to revisit these 1000 points of the EMF research program and investigate the change of RF exposure levels. Spectrum analyzers have been improved in the last years and measurements in the mmWave band could be carried out. mmWave is a new band that will be used worldwide. Investigation into the antennas' emissions of the forthcoming smart devices (e.g., self-driving cars, smart homes) could be a valuable project to ensure human protection and provide special guidelines if needed.

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