Chapter 9 is retrieved on 10 May 2019 from my 'Wiley’ book ‘Radio Spectrum Management: Policies, Regulations and Techniques'; see Amazon. The Author serves as ITU intersectoral activities on RF-EMF and initiated the ITU 32 comments to ICNIRP public consultation, to revise the 1998 ICNIRP Guidelines. ICNIRP and IEEE will soon revise their EMF limits. Dr. Haim Mazar, 10 May 2019

08 March 2016

Chapter number 9

9. Chapter Title: Limitations to Radio Frequency Human Exposure

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9.1 Human Hazards

The proliferation of cellular base stations and wireless fixed installations around the world, the public dislike of large antenna structures and the growing concern against electromagnetic pollution has led to constraining legislations and regulations to ensure protection of the public. Human-hazards have become a significant health and safety issue to regulators, service providers and wireless equipment suppliers. Populations are exposed to electromagnetic fields (EMF), the levels of which continue to increase due to more wireless systems (such as Wi-Fi) and as technology advances; e.g., LTE operation may increase the human exposure by 20%. Limitations to Radio Frequency (RF) human exposure contain restrictions on exposure that are intended to assist those with responsibility for the safety of the general public and workers. The dominant sources of human exposure to RF radiation are near-field wireless sources for workers; and transmitters operating on or in close vicinity to the body, such as hand-held devices, for the general population. Wireless communications use electromagnetic waves in RF ranges of the spectrum, which are of much lower frequencies compared to ionizing radiation\(^1\), such as X-rays or Gamma-rays. As such, RF waves do not have enough energy to either break molecular bonds or even cause ionization of atoms in the human body; hence, their classification as non-ionizing radiation (NIR). The short-term thermal heating capabilities of RF (e.g., microwave ovens) are well known. The question is whether there are some other long-term health effects, e.g., cancer. While some studies have indicated the possibilities of non-thermal effect in living organism, they have never been substantiated. The international commission on non-ionizing radiation protection (ICNIRP)\(^2\) states: ‘It is the opinion of ICNIRP that the scientific literature published since the 1998 guidelines has provided no evidence of any adverse effects below the basic restrictions’; see ICNIRP 2009 Statement. It is known that radio waves, at current frequency ranges used on mobile phones, cause vibration of polarised molecules, e.g. water, and thus through induced friction forces they cause heat to be developed at tissues surrounding the device’s antenna. On the other hand, the international agency for research on cancer (IARC)\(^3\) took a more conservative approach by labelling Radio Frequencies (RF) as Category 2B; i.e., ‘possibly carcinogenic to humans’ (World Health Organization WHO 2011). In terms of mobile phones and cancer, and environmental exposures from transmitters the World Cancer Report 2014 says:

- ‘No consistent association has been found between use of mobile (cell) phones and brain tumours’;
- ‘Therapeutic ionizing radiation is the only proven cause of brain cancer. The use of mobile phones remains under investigation’;
- ‘Associations between heavy use of mobile phones and certain brain cancers have been observed, but causal interpretation is controversial; more data are needed, particularly on longer-term use of mobile phones’; and
- ‘With regard to environmental exposures from transmitters, including television, radio, and military transmissions as well as mobile phone networks, the evidence is inadequate

---

\(^1\) Electromagnetic radiation at frequencies above the ultra-violet band are classified as ‘ionizing radiation’, because when incident on matter they have enough energy to effect changes in the atoms, by liberating ionizing electrons and thus altering their chemical bonds. Ionizing radiation occurs at frequencies above 2.900 THz (2.900×10\(^9\) Hz). This frequency limit corresponds to a wavelength of about 103.4 nm; and minimum ionization energy of 12eV. Plank constant relates the electromagnetic radiation to the frequency of that radiation. Proof of \(f_{\text{basic}}\): since Plank constant \(h\) equals 4.135 667 516 x 10\(^{-15}\) electron-Volt second, and the Plank-Einstein relation energy \(e=hf\), the minimum frequency \(f\) of ionizing radiation 12/(4.135 667 516 x 10\(^{-15}\)) equals 2.9 x 10\(^{15}\) Hz, 2.900 TeraHz.

\(^2\) ICNIRP is an international body of independent scientific experts specialized in non-ionizing radiation protection. ICNIRP addresses the important issues of possible adverse effects on human health of exposure to non-ionizing radiation

\(^3\) IARC is an inter-governmental and inter-disciplinary agency, whose objective is to promote international collaboration in cancer research. IARC is part of the World Health Organization of the United Nations.
due to lack of high-quality studies with accurate individual exposure assessment’. The main tool for RF gauging the impact of NIR on human tissues is the ‘Specific Absorption Rate’ (SAR), i.e. average RF power absorbed in a unit mass of the human tissue; ‘electric field-strength’ and ‘power-density’ parameters are directly derived from SAR and serve to calculate and measure the human exposure from base stations. ICNIRP 1998 ‘guidelines for limiting the exposure to time varying electric, magnetic and electromagnetic fields (up to 300 GHz)’ defines these fields as EMF, and indicates the ‘basic restriction’ for:

. Some countries (and cities) adopt higher profiles (lower RF thresholds) which lead to severe restrictions on EMF, that are at odds with those of the international community. ICNIRP guidelines are backed by WHO, and constitute the current scientific consensus. Nevertheless, national regulations have a priority status in their countries; as influenced by social-economic-political factors, the values adopted in each country may vary. This chapter is a specialist area; it is significant to the spectrum managers and policy makers, as stringent policies, regulations and approaches affect the provision of radio services. There are countless studies on EMF risks; this chapter focuses on policies and regulations without entering the biological arena. Despite ICNIRP 1998 guidelines to limit the exposure to EMF, parts of the public have remained concerned, on the basis that there exists no proof that ICNIRP threshold levels are safe, as no all possible health effects were studied. While, absolute proof does not logically exist, national regulators are placed under public pressure. To answer this dilemma, some countries apply the precautionary-principle to restrict the human-hazards thresholds. As an example, the UK Regulator formed the Stewart Committee, which consisted of a group of independent experts; the committee recommended applying the precautionary-approach to the EMF health risk management problem. This approach may replace the two-state risk management model (above/below the threshold), allowing the introduction of other factors; it is a trade-off balance between the remaining uncertainty (and the damage in the case that the worst-case turns true), versus implementing stricter requirements (resources and reduced quality of service).

Using the example of the international ionizing radiation basic safety standards developed as a collaborative approach between different UN organisations, WHO is considering developing an international standard for EMF exposure according to the International EMF Project Progress Report 2013-2014.

9.2 RF Health Risks as a Social Story

9.2.1 Electromagnetic hypersensitivity and electrophobia

The EMF controversy is a social issue more than a strictly scientific one, as safety is a concept that is more social than scientific. Evidence is propelled by feelings and beliefs derived from values, moral principles and knowledge, rather than facts established by result of studies of biological processes. Also, the reaction of people is selective and inconsistent; we live in a society shaped by consumer health and ecological anxieties. Psychology may explain why some people react negatively toward newly deployed technologies. It is sometimes quite an

---

4 ‘ICNIRP reconfirms the 1998 basic restrictions in the frequency range 100 kHz–300 GHz until further notice (ICNIRP 2009 Statement p.257)’.

5 ICNIRP 1998 uses the terms ‘basic restriction’ for SAR and current density, and ‘reference levels’ for EMF, whereas EU directive 2004/40/EC and CENELEC ENs use the terms ‘limits’ for SAR and ‘action values’ for EMF; ANSI/IEEE C95.1-2006 Std uses the term ‘SAR limits’ and ‘maximum permissible exposure’ (MPE) limits.
irrational attitude (and phobia?) associated with a number of possible hazards; e.g. the invisible EMF can be compared to a childish fear of the dark and the unknown, a ‘phantom risk’.

Although no causal link with exposure to electromagnetic fields or waves has been established, individuals report a variety of health problems and mild symptoms, and react by avoiding the RF fields as best they can; others are so severely affected that they cease work and change their entire lifestyle. This reputed sensitivity to EMF has been generally termed ‘electromagnetic hypersensitivity’ (EHS). EHS is characterized by a variety of non-specific symptoms, which afflicted individuals attribute to exposure to EMF. The symptoms are certainly real and can vary widely in their severity; see WHO 2005. WHO recognises that EMF intolerance is a medical condition, and that electro sensitivity is a clinical situation, whereby sufferers are entitled to compensation. The council of Europe, Resolution 1815 (2011) §8.1.4 recommends that member states “pay particular attention to ‘electrosensitive’ people who suffer from a syndrome of intolerance to electromagnetic fields and introduce special measures to protect them, including the creation of wave-free areas not covered by the wireless network”. EMF hypersensitivity can occur as a bona fide environmentally inducible neurological syndrome; see conclusion of Int J Neurosci. 2011. Countries may set areas electrosanitized, so persons with electro hypersensitivity may have the opportunity to live and work in an electrosanitized environment. As will be described in a subsequent paragraph 9.7.3, the common public fear is also based on many myths, which are not in line with reality.

9.2.1 Regulating uncertain risks

The main concern for regulators is about regulating uncertain risks from electromagnetic fields radiating from mobile phones, cellular or broadcasting towers and amateurs' transmitters. The significant precedent for reactions against cell-phone emissions was propelled by suspicions about electricity pylons⁶; similar ecological pressure groups are campaigning against both types of radiation. The opposition to the erection of both ‘threats’ are developed on a largely economic and classically environmental basis. Demands for relocation of these ‘polluters’ are based on health fears, as much as on concern about their impact on the devaluation of property prices, open fields, beauty of the landscape (impact on visual amenity) and even democracy's factor- their construction without consultation (Burgess 2006 p.339).

The management of RF human-hazards is a problem of reconciling the roles of science (by the 'weight of evidence', i.e., the ICNIRP threshold levels) and risk assessment (the adopted values of each country). Science is the most powerful, objective and effective agent to provide a universal base for systematic knowledge. However, by definition, science cannot prove the ‘null’ or ‘empty’ group: in our case, the inexistence of harm. Hence, ‘it is impossible to scientifically prove absolute safety (the null hypothesis)”; see the Institute of Electrical and Electronic Engineers IEEE⁷ standard (Std) also approved by the American National Standards Institute (ANSI), ANSI/IEEE C95.1-2006 p.79. For example, ‘with regard to non-thermal interactions, it is in principle impossible to disproove their possible existence but the plausibility of the various non-thermal mechanisms that have been proposed is very low” (ICNIRP 2009 Statement p.257). The national thresholds and recommended limits are related to the national tolerability to risks, governmental and policy orientations. The adopted thresholds reveal the public trust (the Commentary of Slater in Lofstedt and Vogel 2001 p.410), the level of confidence in their states and institutions, and in their ability to resolve problems (Burgess 2003 p.15 and 2004 p.14). Trusting styles (of the public toward the regulator) may lead to less precaution (and thus higher threshold levels, or none at all), while more antagonistic styles

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⁶ Utility transmission lines (power lines) and high power apparatuses (generators, transformers) produce magnetic and electrical fields; see Mazar 2009 pp .24-5. Tables 6 and 7 row 3 in ICNIRP 1998 p.511 and updated ICNIRP 2010 Table 4 p.827 specify the reference levels at extremely low frequencies (ELF) 50-60 Hz; much lower RF than the broadcasting and cellular radiations.

⁷ IEEE includes the International Committee on Electromagnetic Safety (ICES) focused on development and maintenance of EMF safety standards.
(including mistrust of regulators and public toward science) lead to lower protection thresholds (meaning more restrictive emissions). Moreover, trusting is linked to the presumption of innocence; less precaution is typical to the ‘innocent until proven guilty’ way of thinking: there are no EMF hazards to the health of humans until the risks are scientifically determined and proven. In contrast, the more restrictive countries presume worst-case scenarios and that EMF are ‘guilty until proven not-guilty’: RF emissions cause severe human-hazards; therefore, the RF limits to exposure levels should be reduced. The conflicting policies are also derived from different rationalities and worldviews (Mazar 2009 p. 200).

Paragraph 4.1.1.1 ‘Zero Risk and Risk-versus-Risk in Regulating Uncertain Risks’ already discussed the risk to flight safety, versus the risk of being disconnected; thus, when operating handheld small personal electronic devices (PEDs) on board. Important to note that mobile phone users tend to be exposed to much higher levels of radiation from their handsets than from masts, because we are much closer to the RF source. The main societal difference between the radiation from the cellular terminal (SAR) and base station is that the cellular utilisation is voluntary (it is our choice to use cellular phone) and the base station’s emission is involuntary. Chauncey Starr (1969 pp. 1232-8) proposed three tentative laws providing a quantitative instrument:

. The first law (the public is willing to accept voluntary risks) explains that the persons fighting against the cellular towers do nevertheless use cellular phones; since individuals are freely allowed to incur danger that threatens only themselves;
. The second law (the acceptability of risks appears to be roughly proportional to the real and perceived benefits) probably explains the positive perception of cellular activity in the Scandinavian countries (benefits to industry); and
. The third law (the acceptable level of risk is inversely related to the number of persons exposed to that risk) emphasises administrations' concern, regarding more than 8 billion users of cellular phones and millions of base-stations worldwide.

The global interest of public and Administration boosts international activities; The Plenipotentiary Conference (Busan, 2014), which is the top policy-making body of the International Telecommunication Union (ITU), updated Resolution 176 (Rev. Busan, 2014) ‘human exposure to and measurement of electromagnetic fields’ and ITU-D approved 2014 report on Question 23/1 ‘strategies and policies concerning human exposure to electromagnetic fields’.

9.3 RF (Radio Frequency) exposure and thermal damage

9.3.1 Human-Hazards: Risks from RF Exposure

Standards for non-ionizing radiation (NIR) exposure limits\(^8\) are the formal instruments taken by governments to limit both the occurrence and the resulting consequences from potentially risky exposures to EMF generated by radiating emitters. Radiological electromagnetic standards ‘race to the bottom’ in reducing thresholds, i.e. in 1995 the European committee for electrotechnical standardisation (CENELEC) established the European limit to the EMF power-density level\(^9\) 9 W/m\(^2\), at 900 MHz, and since June 2000 the European Commission (EC) adopted the ICNIRP 1998 level of \(\frac{f(\text{MHz})}{200} =\) 4.5 W/m\(^2\). Before the 21\(^{st}\) century, emissions from wireless terminals of less than 7 Watts were not controlled; in contrast, at

---

\(^8\) Recommendation ITU-T K.70 p.3 provides this definition for NIR exposure limits ‘values of the basic restrictions or reference levels acknowledged, according to obligatory regulations, as the limits for the permissible maximum level of the human exposure to the electromagnetic fields’.

\(^9\) The former UK national radiological protection board (NRPB; was incorporated in the health protection agency (HPA) on 1 Apr 05) limited the power-density level of human-hazards (NRPB 1993 volumes 4 and 5) in the GSM900 band to 8.2 higher than the ICNIRP 1998 and European threshold. Adopting the 'NRPB 2004: Recommendation 131' in the UK today, the emissions from cellular base stations meet the ICNIRP 1998 guidelines for public exposure. See also Recommendation ITU-R BS.1698 p.67 Table 9, which compares the power-density levels from the three renowned institutions.
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present, a typical cellular handset (UMTS or LTE) transmitting at a maximum of 200 mW undergoes regulatory testing. More societal concerns, more awareness, less public tolerability to health risks and the precautionary-principle explain this more restrictive approach; the lower limits are also a result of media campaigns and some regulatory rivalry (the low exposure levels in Italy, for example).

9.3.1.1 RF Exposure Units and Standards
Table 9.1 lists the reference units of the physical quantities used at the engineering analysis on human-hazards; as in Table 5.1 in chapter 5, the units are mainly based on the international system of units (SI); see BIPM (Bureau International des Poids et Mesures) 2006.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>$F$</td>
<td>Hertz</td>
<td>Hz</td>
</tr>
<tr>
<td>Electric field-strength</td>
<td>$E$</td>
<td>Volt per metre</td>
<td>V/m</td>
</tr>
<tr>
<td>logarithmic term</td>
<td>$E$</td>
<td>dB(V/m)</td>
<td></td>
</tr>
<tr>
<td>Magnetic field-strength</td>
<td>$H$</td>
<td>Ampere per metre</td>
<td>A/m</td>
</tr>
<tr>
<td>logarithmic term</td>
<td>$H$</td>
<td>dB(V/m)</td>
<td></td>
</tr>
<tr>
<td>Magnetic flux-density</td>
<td>$B$</td>
<td>Tesla</td>
<td>T</td>
</tr>
<tr>
<td>Power</td>
<td>$p$</td>
<td>Watts</td>
<td>W</td>
</tr>
<tr>
<td>logarithmic term</td>
<td>$P$</td>
<td>dBW</td>
<td>dBM is practical</td>
</tr>
<tr>
<td>Power-density or power flux</td>
<td>$S$</td>
<td>Watt per square metre</td>
<td>W/m²</td>
</tr>
<tr>
<td>density</td>
<td></td>
<td>mWatt per square cm</td>
<td>mW/cm²</td>
</tr>
<tr>
<td>Specific Absorption Rate</td>
<td>SAR</td>
<td>Watt per kilogram</td>
<td>W/kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mWatt per gram</td>
<td>mW/g</td>
</tr>
</tbody>
</table>

Generally there are two types of potentially adverse effects: thermal and non-thermal. Thermal effects are caused by a malfunction of the body’s thermo-regulation system, when it becomes unable to regulate the raise of human tissue temperature (due to the heat absorbed by the EMF) over the body’s core temperature (about 36.5°C). Non-thermal effects are produced by interaction mechanism between the EMF and biological tissues or system, at power-density levels that do not necessarily increase significantly the tissue temperature. ICNIRP 1998 restrictions are based on established and measurable health effects, i.e. based only on thermal effects; as the potential adverse impact of the non-thermal effect has never been established and remains controversial.

Between 100 kHz and 10 GHz, ICNIRP basic restrictions on SAR are provided to prevent whole-body heat stress and excessive localized tissue heating. ICNIRP 1998 basic restrictions on biological and health effects above 10 MHz are derived from a body temperature rise of more than 1°C. ‘This level of temperature increase results from exposure of individuals under moderate environmental conditions to a whole-body SAR of approximately 4 W/kg for a time duration of about 30 minutes. A whole-body average SAR of 0.4W/kg has therefore been chosen as the restriction that provides adequate protection for occupational exposure. An additional safety factor

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10 ICNIRP 1998 p.508 details: ‘The occupationally exposed population consists of adults who are generally
of 5 is introduced for of the general public, resulting in an average whole-body SAR limit of 0.08 W/kg (ICNIRP 1998 p.509). A factor of 50 provides adequate protection for exposure of the public (ICNIRP 2009 Statement p.257).

9.3.1.2 ICNIRP 1998 and ICNIRP 2010 Reference Levels

Quoting ICNIRP 1998 p. 495: ‘Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.’ The ICNIRP 1998 reference levels are accepted worldwide and countries’ thresholds are compared to these reference levels.

ICNIRP 1998 p.511 tables 6 and 7 define the exposure thresholds; the World Health Organization (WHO) adopts these limits as their reference for EMF. The following Tables and Figures specify the reference ICNIRP levels at different frequencies; the exposure values in the figures are general public and occupational exposure. Below 10 MHz (wavelength 300 meters), effects on human body are due to mostly near-field conditions; the reference levels are provided mainly for the electric field-strength (V/m)12. Between 10 MHz and 300 GHz the basic restrictions are also provided on the basis of power-density (W/m^2), to prevent excessive heating in tissue at or near the body surface. As mentioned above, the power-density of the general public exposure is 5 times lower than the occupational exposure.

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11 Exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. By contrast, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals’.

12 The two magnetic: H-field-strength and B-flux-density are related; however in the near-field case, B and H are not. This chapter refers only to RF human exposure and does not deal with the extremely low frequency (ELF) fields in 50/60 Hz, produced by high power apparatuses (generators, transformers, etc.) and utility transmission lines (power-lines); therefore, H and B are not mentioned.
### Table 9.2: ICNIRP 1998 reference levels for occupational and general public exposure

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Electric field-strength (V/m)</th>
<th>Equivalent plane wave power-density $S_{eq}(W/m^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>general public</td>
<td>occupational</td>
</tr>
<tr>
<td>1-25 Hz</td>
<td>10,000</td>
<td>20,000</td>
</tr>
<tr>
<td>0.025-0.82 kHz</td>
<td>250/f(kHz)</td>
<td>500/f(kHz)</td>
</tr>
<tr>
<td>0.82-3 kHz</td>
<td>250/f(kHz)</td>
<td>610</td>
</tr>
<tr>
<td>3-1,000 kHz</td>
<td>87</td>
<td>610</td>
</tr>
<tr>
<td>1-10 MHz</td>
<td>$87/f^{1/2}$ (MHz)</td>
<td>$610/f$ (MHz)</td>
</tr>
<tr>
<td>10-400 MHz</td>
<td>28</td>
<td>61</td>
</tr>
<tr>
<td>400-2,000 MHz</td>
<td>$1.375f^{1/2}$ (MHz)</td>
<td>$3f^{1/2}$ (MHz)</td>
</tr>
<tr>
<td>2-300 GHz</td>
<td>61</td>
<td>137</td>
</tr>
</tbody>
</table>

**Figure 9.1** ICNIRP 1998 electric field-strength for occupational and general public exposure
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Figure 9.2 ICNIRP 1998 power-density reference levels; above 10MHz only ICNIRP 2010 ‘Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)’ updated the reference levels till 100 kHz (only). ICNIRP 2010 Table 4 includes reference levels till 10 MHz; however, due to the Note “In the frequency range above 100 kHz, RF specific reference levels need to be considered additionally” and the title of ICNIRP 2010, the reference to ICNIRP 2010 ‘stops’ at 100 kHz; Administrations may use ICNIRP 2010 reference levels till 10 MHz; see Report ITU-R SM.2303-1 (2015) section 8 (written by the author), referring to both guidelines, even between 100 kHz and 10 MHz. The electric field-strength unit at the original ICNIRP 2010 is kV/m, instead of V/m. ICNIRP 2010 Tables 2 (occupational exposure) and 4 (general public exposure) are quite different than ICNIRP 1998. Figure 9.3 compares ICNIRP 2010 and ICNIRP 1998 reference levels till 10 MHz.

Figure 9.3 Reference levels: ICNIRP 2010 compared to ICNIRP 1998 till 10 MHz

Even that the assumptions are not completely identical.
The following Table specifies ICNIRP 1998 and ICNIRP 2010 ‘reference levels’ for occupational and general public exposure up to 400 MHz. Assuming that ICNIRP 2010 guides only till 100 kHz, this is the compound international level for all frequencies up to 400 MHz.

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Electric field strength (V/m)</th>
<th>Magnetic field strength (A/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>general public</td>
<td>occupational</td>
</tr>
<tr>
<td>3-100 kHz*</td>
<td>83</td>
<td>170</td>
</tr>
<tr>
<td>3-150 kHz</td>
<td>87</td>
<td>610</td>
</tr>
<tr>
<td>0.15-1 MHz</td>
<td>10</td>
<td>87</td>
</tr>
<tr>
<td>1-10 MHz</td>
<td>87/1² (MHz)</td>
<td>610/1² (MHz)</td>
</tr>
<tr>
<td>10-400 MHz</td>
<td>28</td>
<td>61</td>
</tr>
</tbody>
</table>

*Only the first row in the table is of ICNIRP 2010; other rows are ICNIRP 1998.

The effect on the nervous system (nerve stimulation) is dominant at low-frequency range extending from 1 Hz to 100 kHz; above 100 kHz, effects such as heating are considered. Therefore, although ICNIRP 2010 is valid till 100 kHz; for the frequency range from 100 kHz up to approximately 10 MHz protection from both, low frequency effects on the nervous system as well as high frequency effects need to be considered, depending on exposure conditions.

Those are main differences between the 1998 and 2010 guidelines, till 100 kHz. The ICNIRP 2010 reference levels relative to ICNIRP 1998 are more liberal for the magnetic-field and more restrictive for the electric-field below 50 Hz:

- Electric field-strength: at 25 Hz ICNIRP 1998 level equals 10,000 V/m and ICNIRP 2010 level equals 5,000 V/m;
- Magnetic field-strength at 3-100 kHz ICNIRP 1998 level equals 5 A/m and ICNIRP 2010 level equals 21 A/m.

9.3.1.3 Exposure levels near-field: cellular handsets

The general public receives the highest exposure from handheld devices such as mobile phones, which deposit most of the RF energy in the brain and surrounding tissues; typical environmental exposures to the brain from handsets are several orders of magnitude higher than those from mobile-phone base stations on rooftops or from terrestrial television and radio stations. As far as exposure levels are concerned, a distinction is made between the fixed radiating transmitters of the base stations and the portable handsets. The hazards from fixed transmitters refer to the field-strength and power-density generated, whereas handset hazards are considered mainly by the Specific Absorption Rate (SAR) value. The reason for the two different approaches is that the far-field\(^{14}\) signal (easily simulated and measured) is practical to analyse EMF human exposure, radiated for the fixed wireless stations; whereas the handset, which is used in the proximity of the user’s body; the body configuration in conjunction with the handset design have a strong impact on the EMF so called near-field\(^{15}\). The SAR, related

---

\(^{14}\) Recommendations ITU-T K.91 p.7 and K.61 p.2 define far-field ‘That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In the far-field region, the field has predominantly plane-wave character, i.e., locally uniform distribution of electric-field-strength and magnetic field-strength in planes transverse to the direction of propagation’. More details in section 5.6.7 near-field to far-field.

\(^{15}\) ITU-T K.91 p.8 defines near-field ‘The near-field region exists in the proximity to an antenna or other radiating structure in which the electric and magnetic fields do not have a substantially plane-wave character.
Limitations to Radio Frequency Human Exposure

to the temperature rise due to the EMF, defines the threshold levels for the handsets. In terms of exact definition, the SAR is ‘the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given mass density (ρm)’ (see Recommendation ITU-T K.91); it is expressed in W/kg.

\[ SAR = \frac{d}{dt} \left( \frac{dW}{dm} \right) = \frac{d}{dt} \left( \frac{dW}{\rho m dV} \right) \]  

(9.1)

Table 9.4, see also IARC 2013 p. 116 Table 1.15, compares the absorption levels in ICNIRP 1998. European Community (EC)16 and North America17 in uncontrolled environments; Table 9.4 specifies the exposure limits for the partial body limit for mobile devices18; see also in Chapter 8, Table 8.6.

<table>
<thead>
<tr>
<th>ICNIRP</th>
<th>European Community</th>
<th>USA and Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 10 MHz to 10 GHz;</td>
<td>portable devices;</td>
<td></td>
</tr>
<tr>
<td>localized SAR (head and trunk)</td>
<td>general public / uncontrolled</td>
<td>portable devices;</td>
</tr>
<tr>
<td>2.0; averaged over 10 g tissue</td>
<td>1.6; averaged over 1g tissue</td>
<td>portable devices;</td>
</tr>
<tr>
<td>(it is also ANSI/IEEE C95.1-2006</td>
<td></td>
<td>portable devices;</td>
</tr>
<tr>
<td>level)19</td>
<td></td>
<td>portable devices;</td>
</tr>
</tbody>
</table>

SAR can be ascertained20 in three ways as indicated by the following equations:

\[ SAR = \frac{\sigma e^2}{\rho} = C_i \frac{dT}{dt} = J^2 \frac{1}{\sigma \rho} \]  

(9.2)

For pulsed or brief applications of RF energy, the exposure duration is not long enough for significant conductive or convective heat transfer to contribute to tissue temperature rise. In this case, the time rate of initial rise in temperature (slope of transient temperature response curve) is related to SAR through (see ICNIRP 2009 Vecchia pp. 52 and 60),

\[ SAR = C_i \frac{\Delta T}{\Delta t} \]  

(9.3)

where:

\[ e \] : value of the internal electric field-strength in the body tissue (V/m)

\[ \sigma \] : conductivity of body tissue (S/m) (Siemens per meter, or mho per meter)

\[ \rho \] : mass density of body tissue (kg/m³)

\[ C_i \] : heat capacity of body tissue (J/kg °C)

but vary considerably from point to point’. The reactive near-field of an antenna with maximum extension D is defined as Max(λ, D, \( \frac{D^2}{4\lambda} \)) where λ denotes the wavelength; to be compared to the Fraunhofer distance defining the far-field boundary of directive antennas as 2 \( \frac{D^2}{4\lambda} \).  

16 References: ICNIRP 1998 p.509 Table 4; 1999/519/EC Annex III, Table 1 and IEC 62209-1 ed1.0; IEEE 1999 p. 29.

17 FCC 1997 OET Bulletin 65 p. 75 (FCC 2012 CFR 47 FCC § 2.1093) and 1999 Canada Safety Code 6. NOI FCC 13-39 or R&O FCC 03-137 2013 keeps the SAR levels unchanged; see 8.3.4.4 Indicators of the USA.

18 Moreover, for frequencies above 6 GHz currently used exposure limits of FCC and ICNIRP are not consistent, i.e. there are inconsistencies between SAR and power-density basic restrictions at the transition frequency.

19 Based on email from Lira Hamada (Ph.D.) National Institute of Information and Communications, Tokyo- on 27 July 2014, this is also the level in Japan.

\[ \frac{dT}{dt} : \text{time derivative of temperature in body tissue (°C/s)} \]

\[ J : \text{value of the induced current density in the body tissue (A/m}^2\text{)} \]

\[ \Delta T : \text{temperature increment (°C)}; \]

\[ \Delta t : \text{pulse width or duration of RF exposure (s)} \]

Threshold levels for the maximal peak are set by manufacturers according to international standards and it is difficult for national regulators to deviate. The handset is working in full output power in the worst connection conditions (obstacles or long distance to base station) and in minimum output power in the best connection conditions (line of sight and close to the base station).

The maximum SAR level for different mobile phones varies according to technology; SAR is also influenced by technical parameters such as the antenna used and its placement within the device. The SAR information for a mobile phone is available from the mobile manufacturers’ forum website [http://www.sartick.com](http://www.sartick.com/).

### 9.3.1.4 Simulations and Tests of mobile phones

The near-field SAR measurements are complicated and require advanced instrumentation techniques to carry them out. SAR measurements are carried out according to the standardized protocols. Main international measurement standards for measuring the SAR in the human head are the International Electrotechnical Commission (IEC)\(^{21}\) IEC 62209-1 and IEEE 1528 standards. SAR measurements are exclusive, relative to the power-density and field-strength measurements in the far-field. In view of the interaction between the EMF and the user body, SAR levels are measured by using a so-called ‘phantom’, which represents the human head (Kuster, Balzano and Lin 1997 p.21). IARC 2013 p. 58, fig. 1.12 specifies variation in SAR as a function of frequency in adult and child phantoms. Due to the closer proximity of the phone to the brain of children compared with adults, the average exposure from use of the same mobile phone is higher by a factor of 2 in a child’s brain and higher by a factor of 10 in the bone marrow of the skull; see IARC 2013 p. 408.

The mobile phones are tested for compliance at their highest possible power level through rigorous tests and multiple SAR measurements. Handsets rarely operate at maximum power levels during everyday use; therefore SAR values reported for each model of mobile phone tend to overstate real-life exposure levels. Each model of mobile phone is tested using internationally agreed testing procedures as outlined in relevant standards. The handsets are tested using both a ‘phantom’ head and a separate ‘phantom’ torso for body-worn measurements. The phantoms are filled with liquids that simulate human tissue, such that the relevant electrical properties are similar to the human tissues. SAR values are measured with the phone at its different operating frequencies and in a range of positions. A probe inside the liquid measures the electric field-strength inside the phantom, and uses this to determine the maximum SAR value for the model of phone in each particular configuration. As a result, the testing is both complex and time consuming; for full compliance testing, the process can take up to several weeks depending on the model in question.

Figure 9.4 (source: Holon Institute of Technology) depicts SAR phantom simulations, 900 MHz, 0.5 Watt emission. Figure 9.4 shows the numerical SAR simulation of peak spatial SAR distribution in a magnetic resonance imaging (MRI) based human head phantom, normalized to 1W antenna input power. The location of the maximum SAR depends on the antenna structure, head anatomy and operating frequency. At Figure 9.4, the spatial peak (the area in red) occurs close to the surface at the ear where the handset is placed. The ICNIRP 1998 EMF

\(^{21}\) When ICNIRP was established, IEC was expected to develop human exposure guidelines; but there was a clear agreement between ICNIRP and IEC to share responsibility: ICNIRP focuses on exposure guidelines development and IEC on exposure assessment standards.
exposure limit for the head peak spatial average SAR is 2 W/kg, where the compliance measurements/calculations are compared to. The penetration of the RF EMF in the human head is rapidly slowed down due to the high attenuation of propagation of RF fields in the human tissues.

Figure 9.4 Numerical simulation of Specific Absorption Rate (SAR) Based on MRI based head model, Figure 9.5 depicts another SAR simulation\textsuperscript{22}. The spatial peak SAR distribution at 900 MHz for a three years child, generated by a half-wave dipole antenna, normalized to 1W antenna input power. The spatial peak SAR distribution is 0.096 W/kg. The other values are normalized and shown as dB below 0.096 W/kg; the scale is inserted in the graph. As mentioned, maximum average power levels of realistic devices are less than 0.2 W, and in realistic scenarios significantly lower than these values. It should be noted that the SAR averaging is performed as numerical post processing. Depending on the applicable limits, the 1g and 10g averaging SAR’s are calculated in a cubical volume around the maximum spatial peak SAR, as defined in IEEE 1529\textsuperscript{23}.

\textsuperscript{22} The two figures (9.4 and 9.5) of SAR simulations and measurements were prepared by Dr. Jafar Keshvari, Adjunct professor of Bio-electromagnetics, Aalto University, Helsinki-Finland.

\textsuperscript{23} Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure
Figure 9.5 Numerical simulation of SAR; for a three years child

Figure 9.6 is a plot of real measurements; typical SAR measurements result for a commercial mobile phone device; the results are lower than 2 and 1.6 W/kg.

In 2013, the French ANFR measured the SAR of 77 cellular terminals (15% were 4G), see *Rapport annuel 2013* p. 44. No measurement exceeded the ICNIRP 1998 threshold of 2 W/kg. Nearly 89% of monitored terminals’ SAR were less than 1 W/kg (twice lower than the regulatory limit), and 100% were less than 1.5 W/kg; the average SAR value was 0.56 W/kg, and 1.377 W/kg the highest measured value.
9.3.1.5 Exposure levels far-field: fixed radiating stations

For fixed radiating stations, Table 9.5 and Table 9.6 refer only to the exposure limits for general public, unperturbed and uncontrolled environment (unlike the workers/ controlled/ occupational case), as it is the most significant to the public and to the regulator. ICNIRP 1998 (p. 511 Table 6) and EC Directive 2004/40/EC refer to ‘occupational exposure’ (same term is ICNIRP 1998), CFR 47 FCC §1.1310 refers to occupational/controlled exposures and 1999/519/EC to the protection of ‘workers’ (EC). The general public limits of ICNIRP 1998 (p. 511, Table 7) and the European Community 1999/519/EC (Annex III, table 2) are identical, since ICNIRP levels have been endorsed by the European Commission's Scientific Steering Committee. Table 9.5 specifies the closely identical exposure limits of ICNIRP 1998, 1999/519/EC and ANSI/IEEE C95.1-2006 for radiations from (mainly) fixed stations above 10 MHz; see also Table 9.2.

Table 9.5: ICNIRP, EC and IEEE/ANSI reference levels for general public exposure above

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Electric field-strength (V/m)</th>
<th>Equivalent plane wave power-density $S_{eq}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-400 MHz</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>400-2000 MHz</td>
<td>1.375f²</td>
<td>f/200</td>
</tr>
<tr>
<td>2-300 GHz</td>
<td>61</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 9.6 specifies the U.S. Federal Communications Commission FCC (CFR 47 FCC §1.1310) and Japan (Japan 2015 p. 5) above 30 MHz. Table 9.6 details the maximum permissible exposure (MPE) limits for radiating emitters in uncontrolled environment: general public exposure; see also Chapter 8 case studies, human exposure in China and USA.

Table 9.6: USA and Japan general population/uncontrolled exposure

<table>
<thead>
<tr>
<th>Frequency Range (MHz)</th>
<th>Electric-Field (E) (V/m)</th>
<th>Power-Density (S) (mW/cm²)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-300</td>
<td>27.5</td>
<td>0.2</td>
</tr>
<tr>
<td>300-1,500</td>
<td>1.585f^{(1/2)}</td>
<td>f/1,500</td>
</tr>
<tr>
<td>1,500-100,000</td>
<td>61.4*</td>
<td>1</td>
</tr>
</tbody>
</table>

* Only in Japan, V/m is detailed above 300 MHz.

Health Canada is the federal department responsible for protecting the health and safety of Canadians. For its part, Industry Canada is responsible for radio-communication, and has adopted Health Canada’s SC6 limits in its standards and regulations. Health Canada has set limits for human exposure, which are published in a document commonly known as Canada Safety Code 6 (SC6). On 13 March 2015 Health Canada revised the 2009 limits (that were identical to the USA), and published new reference levels: Canada Safety Code SC6 (2015). The new limits are based on the latest available scientific evidence, including improved modelling of the interaction of radiofrequency fields with the human body. The updated

24 ANSI/IEEE C95.1-2006 exposure values in p. 25 Table 9 are similar (not to FCC) to the ICNIRP 1998 level (fMHz/200 W/m²): at 10-400 MHz the IEEE Electric Field (E) and FCC are 27.5 (V/m), compared to 28 (V/m) the ICNIRP 1998. IEEE provides an additional equation above 100 GHz: [(90fGHz-7,000)/200] W/m².

25 The recent FCC §1.1310 radiofrequency radiation exposure limits p. 97 keeps the MPE (and SAR) limits unchanged; see NOI FCC 13-39 or R&O FCC 03-137 2013; FCC has received comments but has not taken further action in this proceeding.

26 The pamphlet reference of 2012 (now 2015: 27 on Heisei year; March 2015) was endorsed by email from Kenichiro Yoshida, electromagnetic environment division radio; department telecommunications bureau, ministry of internal affairs and communications, 1 October 2012. The upper limit in Japan is 300 GHz and not 100 GHz as in USA.

27 FCC uses different units than ICNIRP for power-density: mW/cm² and not W/m²; W/m² = 0.1 mW/cm²

rigorous SC6 science-based limits include slightly more restrictive reference levels in some frequency ranges, to ensure larger safety margins to protect all population, including newborn infants and children\textsuperscript{29}.

Table 9.7 compares the exposure limits in ICNIRP 1998, FCC §1.1310 and the Canada Safety Code SC6; Table 9.7 details the power-density $S_{eq}$(W/m$^2$) thresholds in uncontrolled environment at some relevant RF.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>ICNIRP 1998</th>
<th>FCC §1.1310</th>
<th>SC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 MHz</td>
<td>2</td>
<td>2</td>
<td>1.291</td>
</tr>
<tr>
<td>1.500 MHz</td>
<td>7.5</td>
<td>10</td>
<td>0.02619x$0.6834$=3.88</td>
</tr>
<tr>
<td>3.000 MHz</td>
<td>10 W/m$^2$</td>
<td>0.02619x$0.6834$=6.23</td>
<td></td>
</tr>
<tr>
<td>6.000 MHz</td>
<td>10 W/m$^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

So, Table 9.7 demonstrates that Canada is the most restrictive.

9.3.2 The international, regional and national thresholds; comparative study

Exposure limits in various countries, including Japan, are found at the WHO website: http://www.who.int/docstore/eh-emf/EMFStandards/who-0102/Worldmap5.htm. In addition to the ICNIRP 1998 Guidelines, various institutions define the allowed limits permitted in specific regions, e.g.:

- FCC still utilises\textsuperscript{30} the IEEE Std C95.1-1999. This standard is also approved previously by the ANSI (1992, ANSI/IEEE C95.1);
- IEEE/ANSI standard ANSI/IEEE C95.1-2006 is not approved by FCC; and
- The European Council adopted ICNIRP values, see 1999/519/EC Annex III, Tables 1 and 2.

The national thresholds reveal the regulator’s risk tolerability; see Mazar\textsuperscript{2009} p.12. In the far-field, at 400-1,500 MHz (which includes cellular transmission bands), the maximum allowed power-density level of ICNIRP and Europe for the general public exposure is $f$ (MHz)/200 W/m$^2$ (ICNIRP 1998 p. 511, Table 7). At the 300-1500 MHz range, the U.S. thresholds are $f$ (MHz)/150 W/m$^2$, which is higher by 4/3 (200/150), compared to the ICNIRP 1998 threshold.

Europe addresses RF hazards at the EC R&TTE 1999/5 Directive, i.e. ‘(14) Whereas care should be taken that radio equipment and telecommunications terminal equipment should not represent an avoidable hazard to health’ and Directive 2004/40/EC. Europe in general\textsuperscript{31} follows the ICNIRP 1998 levels, the non-mandatory EU Council Recommendation 1999/519/EC and the base station general public harmonised standard EN 50385/2002. In contrast to the thresholds of power-density from cellular base stations, it is important to observe that North American regulations are more risk averse than 1999/519/EC and ANSI/IEEE C95.1-2006 Std (p.79) in the allowed Specific Absorption Rate (SAR) from the cellular terminal. The ICNIRP 1998 threshold, adopted by EC (EC General Council Recommendation 1999/519) and IEEE Std ANSI/IEEE C95.1-2006 (p.79) is 2.0 W/kg, while the limit in the U.S. CFR 47 FCC § 2.1093 and Canada (Health Canada, Canada Safety Code SC6) is 1.6 W/kg\textsuperscript{32} for the partial body; (see Table 9.4 above).\textsuperscript{16} The North American perception

\textsuperscript{29} Since the publication of SC6, Industry Canada has published various regulatory documents for site compliance and equipment certification: RSS-102: RF Exposure Compliance of Radiocommunication Apparatus (All Frequency Bands); BPR-1: Part I: General Rules - Broadcasting Procedures and Rules; GL-01: Guidelines for the Measurement of RF Fields at Frequencies From 3 KHz to 300 GHz; Towers in your community – Facts about towers.


\textsuperscript{31} Despite an EU Recommendation (WHO 2007 p.129), some EU countries adopt more restrictive thresholds; see WHO ‘EMF world wide standards’.

\textsuperscript{32} Even the averaging is more stringent in the U.S., as the limit is averaged over one gram; see FCC, OET Bulletin 65 p. 40 and OET Bulletin 65 Supplement C p.75, and not 10 grams as in ICNIRP 1998 p. 509.
seems more rational (at least compared to Switzerland and Italy, dividing ICNIRP 1998 power levels up to 100), as the RF radiation power absorbed from the handset is much stronger, being much nearer to the user’s body, compared to the received signal from the base stations; see Mazar 2011.

There is also a difference in the threshold levels among European countries; such a distinction however does not exist in RF standards. Northern Europe is more tolerant than Southern Europe; whereas there are no clear distinctions between Western and Eastern European countries. Switzerland and Italy apply up to 0.01 ICNIRP 1998 reference level for power-density above 2 GHz, acting against proven adverse health effects. Additionally, Switzerland also implements precautionary emission limitations, so-called installation limit values (ILV), at places of sensitive use, such as apartment buildings, schools, hospitals, permanent workplaces and children’s playgrounds. Poland reduces the level by 50 times for public exposure, Luxembourg by 20 times and China is 12.5 times stricter. The U.S. and Japan are the most tolerant in regulating uncertain risks in RF human-hazards. The U.S. and Japan follow the FCC §1.1310 limits for general population /uncontrolled exposure (1.33 ICNIRP level).

9.4 Quantified RF hazards from fixed transmitters

9.4.1 Power-density, field-strength and safety-distances around fixed transmitters

Chapter 5 sections 5.6.2 and 5.6.3 detail the equations to calculate the far-field free-space propagation loss. Enclosed are some useful equations needed at this chapter.

\[
 s = \frac{p_t g_t}{4 \pi d^2} = \frac{\text{eirp}}{4 \pi d^2} \quad (9.4)
\]

\[
 d = \frac{\text{eirp}}{4 \pi s} \quad (9.5)
\]

\[
 e = \frac{\sqrt{30 \text{eirp}}}{d} \quad (9.6)
\]

\[
 d = \frac{\sqrt{50 \text{eirp}}}{e} \quad (9.7)
\]

\[
 \frac{v}{z_o} = \frac{e^2}{120 \pi} \quad (9.8)
\]

where:

- \( p_t \): transmitter power (watts)
- \( g_t \): transmitter antenna gain (numeric)
- \( \text{eirp} \): equivalent isotropically radiated power (watts)
- \( s \): power-density (watts/m^2) (serves as exposure limit)
- \( d \): distance (m)

---

33 See Table 8.6: power-density and SAR uncontrolled environment at 1,000 MHz.
34 ‘Product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna’ ITU Radio Regulations, volume 1 provision 1.161. eirp is not necessarily the product of maximum power and maximum gain; it is the power radiated toward the point of investigation. The cellular transmitters are power controlled and they do not transmit all time at maximal level. Near a cellular antenna, below it, the eirp is low, as a sidelobe in elevation is much attenuated relatively to the antenna main-beam.
\[ e: \text{electric field-strength (V/m) (serves as exposure limit)} \]
\[ z_0^{35}: \text{impedance of free-space, } 120\pi(\text{Ohms}) \approx 377(\text{Ohms}) \]

9.4.1.1 Simultaneous exposure to multiple sources, far-field safety-distance

Equation (9.4) above calculates the power-density and equation (9.6) the field-strength at distance \( d \) from the emitter; both equations indicate that the distance from the radiated source is more significant than the source power level, as the power-density is linear with \( eirp \) and \( 1/d^2 \) with distance. Equation (9.5) calculates the safety-distance \( d \) from the emitter given the power-density threshold \( s \); equation (9.7) calculates distance \( d \) given the field-strength limit \( e \). The safety-distance determines a contour around a specific antenna or mast; this profile determines the public uncontrolled/ unperturbed environment at the far-field. According to equation (9.8) power-density \( s \) and electric field-strength \( e \) are interchangeable (as parameter, not as specific magnitude) and can be replaced; therefore, the RF exposure (limit and measurements) is determined by power-density or the field-strength.

The power-density and the Poynting vector are the vector-product of two vectors: the electric field-strength \( e \) and magnetic field-strength \( h \). The power-density and the two field-strength vectors have a magnitude and direction of the flow of energy, while the transmitted power and safety-distance are just a scalar number. So, power levels from different emitters at the same RF are summed as scalar quantities. In practice, the weighted (see later) power-densities are added (as a scalar sum, not vector sum) at the point of investigation; it is explained as the human-hazards thresholds are derived from the scalar quantity energy (heat).

Normally, regulators adopt the worst-case value; i.e. the maximum safety-distance is calculated, assuming:

- maximum antenna gain: point of investigation (POI) at the main antenna beam in azimuth, and sometimes also in elevation\(^{36}\) (near the antenna, the elevation pattern is much attenuated);
- free-space propagation is usually assumed between the emitter and (POI); even though there might be obstacles between the antenna and POI;
- maximum power of the transmitter: cellular base stations coverage to the edge of the cell and at maximum traffic loading; i.e. all channels transmitting at their respective maximum power setting (see Recommendation ITU-T K.70); and
- weighted power-densities at different RF are summed in scalar quantity, even though power-density is a vector and their sums are not necessarily in-phase.

9.4.2 Emissions transmitted from the same site: multiple-antenna installation

The exposure criteria referred to thermal effect circumstances are frequency depended; see

\(^{35}\) \( z_0 \) relates the magnitudes of electric \( e \) and magnetic \( h \) fields travelling through free-space; \( z_0 \equiv \frac{|e|}{|h|} \); see chapter 5 equation 5.78.

\(^{36}\) The antenna downtilt (up to 10\(^\circ\)) toward mobile telephone or broadcasting receivers affects the RF exposure because the antenna transmitting gain changes.
Table 9.2 and Figure 9.2. For emissions transmitted from one location the cumulative safety-distance and field-strength are calculated, given:

\[ \text{eirp}_{eq} : \text{equivalent cumulative eirp (watts)} \]

\[ d_i : \text{safety-distance from each emitter (m)} \]

\[ d_{eq} : \text{equivalent cumulative safety-distance (m)} \]

\[ s_i : \text{power-density from each emitter (W/m}^2) \text{ index i} \]

\[ s_{th} : \text{power-density limit from each emitter (W/m}^2) \text{ index i} \]

\[ e_i : \text{electric field-strength from each emitter (V/m) index i} \]

\[ e_{th} : \text{electric field-strength limit from each emitter (V/m) index i} \]

9.4.2.1 General case: emissions at different frequency ranges

As already explained, ICNIRP 1998 power-density and field-strength reference levels \((s_i \text{ and } e_i)\) are RF dependent. In the case of emitters with different thresholds, we may define (not mentioned in ICNIRP 1998) the equivalent cumulative safety-distance \(d_{eq}\), which equals the square root of sum of individual square safety-distances \(d_{eq} = \sqrt{\sum d_i^2}\).

From equation (9.5) above, each individual safety-distance equals \(d_i = \frac{\text{eirp}_i}{4\pi s_{th}}\).

The eirp\(_i\) of each emitter is weighted by the inverse of its power-density limit \(s_{th}\), thus the square-root of the weighted sum\(^{37}\) provides the equivalent cumulative safety-distance, \(i.e.\):

\[
d_{eq} = \sqrt{\sum d_i^2} = \sqrt{\sum \left(\frac{\text{eirp}_i}{4\pi s_{th}}\right)^2} = \sqrt{\left(\frac{\text{eirp}_1}{4\pi s_{th1}}\right)^2 + \left(\frac{\text{eirp}_2}{4\pi s_{th2}}\right)^2 + \ldots + \left(\frac{\text{eirp}_n}{4\pi s_{thn}}\right)^2}
\]

(9.9)

For each point of investigation (POI), it is needed to check the compliance for the power-density \(s_i\) (or its electric component \(e_i\)) at each frequency band relative to the threshold \(s_i\) (or \(e_i\)). Based on the total cumulative weighted power-density \(s_i\) (see ITU-R Monitoring handbook 2011 p.517 and ITU-T K.83 p. 11), the total exposure quotient (or cumulative exposure ratio) should be less than 1:

\[
s_i = \sum_{i=1}^{n} \frac{s_i}{s_{thi}} = \frac{s_1}{s_{th1}} + \frac{s_2}{s_{th2}} + \ldots + \frac{s_n}{s_{thn}} \leq 1
\]

(9.10)

The requirement for the total 'cumulative weighted field-strength exposure ration' \(w_i\) (see recommendations ITU-T K.91, K.70 and K.52) is\(^{38}\):

\[
w_i = w_{i} = \sum_i \left(\frac{e_i}{e_{thi}}\right)^2 \leq 1
\]

(9.11)

Given that at a particular frequency \(i\), eirp\(_i\) is the temporal averaged eirp, and eirp\(_{th,i}\) is the eirp threshold relevant to the particular antenna parameters and accessibility conditions, a site is compliant if sum of the normalized eirp\(_i\) of each RF is smaller than 1. The following equation (9.12) is the compliance criterion (see K.52):

\[
\sum_i \frac{\text{eirp}_i}{\text{eirp}_{th,i}} \leq 1
\]

(9.12)

\(^{37}\) sum of squares, where each \((d_i^2) = \frac{\text{eirp}_i}{4\pi s_{th}}\)

\(^{38}\) Even calculated differently, \(s_i\) and \(w_i\) are identical.
Calculations done separately for each frequency range allow evaluating the cumulative exposure ratio.

9.4.2.2 Emissions at the same frequency
For the particular case of emitters transmitting at the same RF, or at a frequency range whose limits are frequency independent (like 10–400 MHz and 2–300 GHz), the power-density limits are equal for all transmitters, emitting at the same frequency range, i.e. in equation (9.9) \( s_{1i} = s_{2i} = \ldots = s_{li} \). Therefore,

\[
d_{eq} = \sqrt{\sum_{i} d_{i}^2} = \sqrt{\sum_{i} \frac{\text{eirp}_i}{4\pi s_{li}}} = \frac{1}{4\pi s_i} \sqrt{\text{eirp}_1 + \text{eirp}_2 + \ldots + \text{eirp}_n}
\]  

(9.13)

The equivalent cumulative eirp is defined as the scalar sum of all the emitters’ power; this equivalent \( \text{eirp}_{eq} = \sum \text{eirp}_i \) is inserted in equation (9.13) to calculate the safety-distance.

\[
d_{eq} = \sqrt{\frac{\text{eirp}_{eq}}{4\pi s_i}} = \sqrt{\sum_{i} \frac{\text{eirp}_i}{4\pi s_{li}}}
\]  

(9.14)

The requirement for the total field-strength and power-density exposure rations \( W_i \) (see ITU-T K.91) and \( s_i \) are:

\[
W_i = \sum_{i} \left( \frac{e_i}{e_j} \right)^2 = \frac{1}{\sum_{i} (e_i)^2} \leq 1
\]  

(9.15)

\[
W_i = S_i = \sum_{i} \frac{s_i}{s_j} = \frac{\sum_{i} s_i}{s_j} \leq 1
\]  

(9.16)

9.5 Simulations and measurements of RF exposure

9.5.1 Calculated safety-distances, worst-case, multiple-antenna installation
For a co-located antenna site of FM audio and TV broadcasting, point-to-point and cellular emitters, the cumulative far-field free-space horizontal safety-distance toward a point of investigation is calculated. Table 9.8 is an Excel output calculating the safety-distances and field-strength from these typical emitters. The worst-case is computed, including the cumulative horizontal safety-distance and field-strength.

---

39 The ‘frequency range’ is the column's title ‘frequency range’ in ICNIRP 1998 reference Tables 6 and 7.
40 For a scenario with antennas installed at one tower, in different levels, the equivalent cumulative safety-distance (and field-strength exposure) is calculated relative to an equivalent weighted altitude at the mast.
41 Calculated differently, but identical solution is derived by equations (9.15) and (9.16); see footnote 38. Therefore, the field-strength ration in Table 9.8 is also the power-density ration.
Table 9.8: Radiations from a co-located site; cellular emitters, point-to-point and broadcasting

<table>
<thead>
<tr>
<th>Transmission System</th>
<th>GSM 900</th>
<th>UMTS 2100</th>
<th>IMT 850</th>
<th>point-to-point</th>
<th>Video TV</th>
<th>Audio FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>891</td>
<td>2,100</td>
<td>800</td>
<td>514</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>ICNIRP 1998, power-density (W/m²)</td>
<td>4.75</td>
<td>10.00</td>
<td>4.00</td>
<td>2.57</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Antenna gain (dBi)</td>
<td>16</td>
<td>18</td>
<td>23</td>
<td>17</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Antenna elevation: real pattern or model</td>
<td><strong>742</strong> 265</td>
<td><strong>TBXLHA</strong></td>
<td><strong>80010302_0824</strong></td>
<td>ITU-R <a href="https://www.itu.int/pub/electro/010013001336.pdf">F.1336</a></td>
<td>ITU-R <a href="https://www.itu.int/pub/electro/01001300699.pdf">F.699</a></td>
<td></td>
</tr>
<tr>
<td>Antenna altitude above ground level (m)</td>
<td>32</td>
<td>45</td>
<td>15</td>
<td>25</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Cable loss (dB)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (Watt)</td>
<td>25</td>
<td>64</td>
<td>40</td>
<td>10</td>
<td>1,000</td>
<td>6,000</td>
</tr>
<tr>
<td>eirp (Watt)</td>
<td>800</td>
<td>3,210</td>
<td>2,000</td>
<td>1,580</td>
<td>39,810</td>
<td>47,660</td>
</tr>
<tr>
<td>Specific safety-distance (m)</td>
<td><strong>3.7</strong></td>
<td><strong>5.1</strong></td>
<td><strong>6.3</strong></td>
<td><strong>7.0</strong></td>
<td><strong>35.1</strong></td>
<td><strong>43.6</strong></td>
</tr>
<tr>
<td>Cumulative safety-distance (m)</td>
<td><strong>3.7</strong></td>
<td><strong>6.3</strong></td>
<td><strong>8.9</strong></td>
<td><strong>11.3</strong></td>
<td><strong>36.9</strong></td>
<td><strong>57.1</strong></td>
</tr>
<tr>
<td>ICNIRP 1998, field-strength (V/m)</td>
<td>41.30</td>
<td>61.00</td>
<td>38.89</td>
<td>31.17</td>
<td>28.00</td>
<td></td>
</tr>
<tr>
<td>Specific field strength at 50 m (V/m)</td>
<td>3.10</td>
<td>6.21</td>
<td>4.90</td>
<td>4.35</td>
<td>21.86</td>
<td>23.91</td>
</tr>
<tr>
<td>Specific field-strength at 50m, ICNIRP 1998 ration</td>
<td><strong>0.08</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.13</strong></td>
<td><strong>0.14</strong></td>
<td><strong>0.70</strong></td>
<td><strong>0.85</strong></td>
</tr>
<tr>
<td>Cumulative field-strength ration</td>
<td><strong>0.08</strong></td>
<td><strong>0.13</strong></td>
<td><strong>0.18</strong></td>
<td><strong>0.23</strong></td>
<td><strong>0.74</strong></td>
<td><strong>1.13</strong></td>
</tr>
</tbody>
</table>
Based on the transmitters’ data of the co-located site in Table 9.8, the following four figures depict worst-case calculations. The safety-distances are horizontal relative to the mast.

Figure 9.7 Cumulative horizontal safety-distance, co-located site; y axis (m)
Derived from Table 9.8, Figure 9.8 depicts the cumulative field-strength exposure ratio, for point of investigation at 50 meter.

---

42 Assuming free-space propagation, maximum antenna gain in elevation and azimuth, maximum transmitters’ power (as an example the UMTS base stations use power control and may transmit up to 12 dB below their maximal power), scalar (and not vector) summation of power-densities.
Figure 9.8 Cumulative field-strength exposure ratio, for point of investigation at 50 meter

The field-strength in Figure 9.9 of each transmitter is depicted in dBμV/m (dBμ). The point-to-point and television antennas’ elevation patterns are based on Recommendations of ITU-R F.1336 and F.699 (see Chapter 5, Fig. 5.23), respectively; the simulations provide conservative values, comparing the calculated patterns to ‘oscillating’ real antenna, such as the IMT 850 (80010302_0824) elevation antenna pattern. The maximal exposure is not down the antenna mast, at the closest point near the station, due to the sidelobe attenuation in elevation, with and without down-tilt.

Figure 9.9 Field-strength (dBμV/m) vs. distance (m) of TV, IMT 850 and point-to-point
Similarly to Figure 9.8, the following figure depicts the separate and the cumulative exposure ratio $W$ of different emitters at a co-located site; see more details at Recommendation ITU-T 2007 K.70 Fig. I.5.

![Graph](image)

**Figure 9.10** Coefficient $W_i$ versus distance for a transmitting site with FM, TV and GSM

Figure 9.11 is derived from EMF-Estimator; see additional details in Recommendation ITU-T 2007 K.70 and Fig. D.2. Depicted two cases: without downtilt, and with 10° downtilt, to show the power-density distribution derived from a typical GSM 900 transmitter.
ICNIRP 1998 public exposure, reference level is 4.5 w/m²

Figure 9.11 Power-density versus horizontal distance at near-field and far-field

The following figure (see also ITU-T 2007 K.70 Fig. 8-1) depicts the coefficient $W_t$ distribution as a function of distance for a transmitting site with multi frequency range emitters: FM, TV and GSM 900 systems.

Figure 9.12 Field-strength coefficient $W_t$ versus distance for a transmitting co-located site
9.5.2 Monitoring human exposure

9.5.2.1 Recommendations and standards on monitoring of human exposure

Monitoring of the human exposure is essential and serves as ‘eyes and ears’ of the regulator. The ITU-R Spectrum Monitoring, Edition of 2011 sub-chapter 5.6 pp. 516-31 specifies non-ionizing radiation measurements. Additional significant information on characteristics of EMF measurements (procedures, techniques and instruments), comparison between predictions and measurements, examples of calculated field-strengths, limits and levels can be found in Recommendations ITU-R BS.1698, ITU-T K.52, K.61, K.70 and K.91. A software EMF-Estimator (Amd.3 (02/2013) is attached to K.70 in order to support its application. The software calculates the cumulative exposure for the reference levels; Figure 11 and Figure 12 are prepared by EMF-Estimator. In addition to real measurements, a continuous software-monitoring of the antennas is significant for effective monitoring and enforcement. Such a program collects information directly from the radio switch networks of the cellular carriers nationwide, in order to complete the cellular radiation measurements.

IEC standard IEC.62233 and EN 62233 specify similar measurement methods for magnetic and electric fields of domestic appliances with regards to human exposure. The differences between the two standards are in the exposure limit values, which are specified as ‘basic limit values and reference values’ in Annex B of each standard. EN 62233 only allows the values specified in ICNIRP 1998; in contrast, IEC 62233 provides two sets of exposure limits, ICNIRP 1998 and ANSI/IEEE C95.1-2006. IEEE Std. C95.7-2005 recommends practice for RF safety programs; additional IEC standards on EMF human exposure are IEC 62311 and IEC 62369.

9.5.2.2 Monitoring of human hazards around the world

National websites such as France ANFR mon cartoradio www.cartoradio.fr and Italy monitoraggio campi elettromagnetici http://www.monitoraggio.fub.it/ illustrate measurements. Monitoring around the world reveals that repeatedly the power-density at common points is less than 1 per cent of ICNIRP 1998 threshold, and equivalently less than 10 per cent of the ICNIRP field-strength; exposure levels due to cellular base stations are generally around one-tenth-thousandth of the guideline levels (ICNIRP 2009 Statement p. 258). Moreover, irrespective of country, the year and cellular technology, exposures to radio signals at ground level were only a small fraction of the relevant human exposure standards. See the two comparative international RF exposure surveys of mobile communication radio base stations: 23 countries across five continents Rowley and Joyner 2012, and 260,000 measurement points near radio base stations in seven African countries Rowley, Joyner and Marthinus 2014. Over the period 2001 to 2004 (WHO 2007 p. 30), the UK Radiocommunications Agency (now part of Ofcom) conducted radio surveys at 289 schools with base stations on or near them. At each school, measurements were made at several locations around the school looking at the GSM 900/1800 frequency bands. The field values were then compared to the ICNIRP 1998 threshold: a compliance factor of 1 would imply that the measured field just complies with the ICNIRP guidelines The highest compliance factor measured anywhere was $3.5 \times 10^{-3}$ ($= 12.2 \times 10^{-6}$ of the power-density), with the 90% of the schools having a highest compliance factor below $2.9 \times 10^{-4}$ $(8.4 \times 10^{-8}$ power-density) – which are very low values indeed: de-minimis. IARC 2013 p. 58 Fig. 1.11 specifies a cumulative distribution of exposure quotients corresponding to 3,321 spot measurements made by Ofcom at 499 sites, where public concern

43 The program implemented since 2010 by the Noise and Radiation Department, at the Israeli Ministry of Environmental Protection enabling the Radiation Commissioner to monitor more than 30,000 UMTS sectors of base stations around the country, and receive all radiation related data from every antenna, 24 hours a day, 365 days a year.
44 As already stated power-density and electric field-strength are interchangeable (but they are not identical); WHO 2007 p. 30, ANFR 2007 and Viel et al. 2009 use V/m, while Salzburg 2002 uses W/m² units.
had been expressed about nearby base stations; the quotient values are median 8.1×10⁻⁶ of ICNIRP 1998 power-density, ranging from the 5th percentile 3.0×10⁻⁸ to 95th percentile 2.5×10⁻⁴.

Two hundred randomly selected people in urban, sub-urban, and rural subgroups have measured on 2005–2006 in France⁴⁵ (Viel et al. 2009; see also IARC 2013 p.14) for 24 hours a day, 184 daily measurements. At the GSM 900/1800 bands most of the time, the recorded field-strength was below detection level (0.05 V/m); 0.05 V/m is 3.63% of the ICNIRP 1998 level at 900 MHz. 12.3% of measurements at the FM band indicate field-strength above the detection threshold; the mean field-strength was 0.17 V/m (Viel et al. 2009 p.552), the maximum field-strength was always lower than 1.5 V/m. Exposures from GSM 900/1800 base stations increased with distance near the cellular transmitters, to a maximum where the main beam intersects the ground. ANFR 2007 reveals that at 2004-2007, the average measurements are less than 2% of the field-strength limit (less than 0.04 % of power-density); more than 75% of the measurements were less than 2% of the field-strength limit, regardless of the frequency band considered.

Measurements of GSM 900/1800 signals were made between 12 November and 19 December 2001 (Salzburg 2002 p. 3; see also IARC 2013 p.113 Table 1.14). At 8 of the total of 13 antenna sites selected at random, the Salzburg assessment value⁴⁶ of 1 mW/m² (0.001 W/m²; equivalent to 0.61 V/m) was exceeded by up to a factor of 40. Furthermore, the analysis of the exposure situations shows that in urban areas the exposure levels for those living near transmitting equipment are on average between 10 and 200 mW/m²; 100 mW/m² is 0.1 W/m², 2.2 % of ICNIRP 1998 level (4.5 W/m²) at 900 MHz and 1.1 % of ICNIRP 1998 level (9 W/m²) at 1,800 MHz. The measurements, as well as the exposure simulations, indicate clearly that an exposure value of 1 mW/m² cannot be complied with, for people living near antenna installations in an urban area, for technical and operational reasons.

9.5.2.3 Field-strength calculations versus measurements

Depending on topography, antenna downtilt and elevation pattern, the radiation signals may have a peak value in horizontal distances in the order of 80 to 120 meters from the mast (see for example Figure 9.11). Antenna beam tilt has an influence on the radiation level in the proximity of the transmitting antenna; it can be generally stated that more downtilt increases radiation levels in the proximity of the transmitting antenna (see ITU-T K.70). The exposure near the base station antenna is usually produced by the vertical antenna sidelobes that emit less power than the main beam. Nevertheless, in cases of small downtilt (e.g., 2 degrees tilt) these sidelobes may contribute the maximum exposure below and near the mast; Figure 9.13 illustrates it by measurements and calculation.

The measurements generated by ANATEL⁴⁷ were performed at RF = 1,875.8 MHz, electrical tilt 8°, mechanical tilt 0° and antenna pattern TBXLA-6565C_1920; see Figure 9.13: dashed red- measured, solid green- calculated). To get the scale of the measured values: the ICNIRP 1998 field-strength at 400-2,000 MHz is 1.375 f¹⁵ (MHz) ≈60 V/m, at 1,875.8 MHz. The maximal measured level is ≈0.4 V/m; i.e. 0.67 % of ICNIRP 1998 field-strength threshold; 0.67 % of ICNIRP 1998 field-strength threshold; 0.004 % of ICNIRP 1998 power-density limit.

---

⁴⁵ On 2006, there were 85.1 cellular per 100 inhabitants; see Mazar 2009 p.140.
⁴⁶ 1 mW/m² is 0.001 W/m². ICNIRP 1998 level is f/200: 4.5 W/m² at 900 MHz and 9 W/m² at 1800 MHz. Thus the Salzburg power-density threshold is 4,500 more stringent than ICNIRP 1998 level at 900 MHz and 9,000(!) more at 1,800 MHz.
⁴⁷ See Linhares, Terada and Soares 2013 Fig. 11 and Linhares A., Terada MAB. and Soares 2014 Fig. 5.
Figure 9.13 Measured (dashed) and calculated (solid) field-strength versus distance

Based on Salzburg measurements, IARC 2013 p. 113 underlines that the distance to the base station site has a poor correlation to the incident exposure; moreover, IARC 2013 p.409 emphasises that distance to a base station is not a good proxy for exposure, due to the considerable variability in characteristics of the antennae, shielding and reflection of the waves.

9.5.2.1 Questions to be asked

Monitoring and theoretical assessments of human exposure of cellular sites around the world reveal that the exposure levels are very low, relative to ICNIRP 1998 reference levels; so, these questions may be raised:

- As there are millions of cellular base stations, approximately one station per thousand subscribers (see footnote 54), do we need to enforce post-installation measurements for any base station at ground level for compliance purposes? and
- Why to monitor ex-ante nationally, if measurements can be made ex-post, after specific demand of worried citizens\(^{48}\)?

As the measurements show very low exposure levels, a ‘shadow’ question is:

- May be ICNIRP 1998 reference levels are too high and administrations may reduce them?

ICNIRP reconfirmed its 1998 RF guidelines in 2009 and started the revision of RF guidelines in 2012. WHO and ICNIRP are closely collaborating to publish the Environment Health Criteria (EHC) monograph\(^ {49}\) by early 2016. This document will be the base for the revision of the ICNIRP 1998 RF exposure guidelines.

9.6 RF Hazards limits and their impact on mobile network planning

LTE operation increases the human exposure in 800 MHz by 20%; see ANFR Rapport annuel 2013 p. 47; the public continues to call to reduce the level of exposure. But, stringent policies, regulations and approaches affect broadcasting and mobile network planning. Protest movements cause important delays in the roll-out of latest cellular technologies.

\(^{48}\) See 4.1.2 central-planning, ex-ante and a-priori, versus market-based, ex-post and a-posteriori approaches.

\(^{49}\) Since November 2014 the author is nominated by ITU-R Study Groups to coordinate the ITU inter-sectorial activities on human- hazards and to review the EHC draft Chapter 2: Sources, measurements and exposures pdf, 1.83 Mb.
9.6.1 Excessive exposure limits affect network planning

If at most of investigation points the measured signal is less than 1% ICNIRP 1998 power-density level, what is the problem? The planning problem arises when people reside near the planned antenna. Administrative calculation of the horizontal safety-distance refers to worst-case scenario: usually assumes free-space loss and disregards the attenuation of antenna gain in elevation. Co-location of several emitters and new technologies increase the safety-distance and restrict mast construction near buildings. Moreover, countries (e.g. Switzerland) reduce by 100 (and Salzburg by 9,000) the power-density level and impose difficulty to the cellular base stations' planning. Decreasing the power-density threshold by 100 (or 9,000), and decreasing the field-strength threshold by 10 (or 95=√9000 in Salzburg) increase the safety-distance by 10 (or 95), for the same emission parameters; see equation (9.7). The conclusion: it would probably be very difficult to achieve exposure values lower than 100 mW/m² (=6.1 V/m) without substantial economic consequences (Salzburg 2002 p.3). Lower RF exposure limits enforce to decrease the eirp, in order to reduce the power-density (and field-strength) near the station, or to extend the distance of the mast from the public; these constraints harm the optimal planning and siting of base stations and antennas.

French simulations on 2G and 3G, see ANFR Rapport annuel 2013 p. 48, have shown that a reduction in exposure from 61 V/m to 0.6 V/m will sharply deteriorate the coverage network and quality of service, in particular in-door; in average 82% less interior coverage in Paris center, less coverage 44% in Grenoble and 37% in Grand-Champ. Higher levels of exposure were tested (1 V/m in Paris and 1.5 V/m in Plaine-Commune) and resulted in degradation of coverage inside buildings (losses of 60-80% in Paris centre and 30-40% in Plaine-Commune). To complete these results, simulations of antenna reconfiguration were conducted in seven cities in France, to estimate the additional number of antennas keeping the 0.6 V/m exposure threshold. The conclusion is that the number of sites would be multiplied at least by three; if taking into account also capacity, quality of service, traffic control and access, the factor will expand above three.

Some administrations and municipalities determine minimum range close to sensitive areas of concern, such as schools, hospitals, apartment buildings, children's playgrounds and permanent workplaces; those restrictions add limitations to the network planning. Note that using the phone in the areas of good reception also decreases self-exposure, as it allows the phone to transmit at reduced power (WHO 2011). In addition to the cellular antenna planning restrictions, lowering ICNIRP thresholds worsen the measurement and enforcement of the signals (Salzburg 2002 p.31).

Lowering the down-link effective power, to reduce RF exposure from the base station, imposes additional sites/masts, in order to preserve the quality of service. More transceivers sites, each with lower RF emission power, reduce the human exposure levels from the fixed base stations (as down-link radiation is decreased) and the up-link handsets emissions (as they are closer to the base station and transmit less power). However, due to regulatory limitations, derived from public fears of cellular base stations, it is difficult to construct additional cellular (and broadcasting) masts. Mazar 2009 (Table 4-2 p. 110) compares and contrasts the e-Communications in EU and Comunidad Andina de Naciones (CAN): EU and CAN in South America define the RF spectrum as ‘scarce resources’; however, CAN adds also the physical facilities, as ‘scarce resources’.

50 Such as multiple antennas at the transmitter MIMO: multiple-input and multiple-output.
51 In addition to Salzburg in Austria, Perugia and Novara (WHO 2007 p.145) in Italy limit the field-strength to 3 V/m (7.3 % ICNIRP field-strength and 0.5 % power-density) and 1 V/m (2.4 % ICNIRP 1998 field-strength and 0.06 % power-density) respectively.
52 This is not the case in Italy: the limits are fixed by the national government. No municipal, provincial or regional council are permitted to modify anything; values as 3 V/m and 1 V/m do not exist in Italy.
53 40 dB attenuation: a factor of 100 in field-strength and 10,000 in power-density.
9.6.2 Handling low exposure thresholds by additional cellular antennas or additional RF Spectrum

In average, roughly every 1,000 subscribers need one cellular mast\(^{54}\). The public and cellular operators are much interested in coverage and capacity of the cellular networks. For a given network (technology, number of sites, RF spectrum, quality of service), better coverage is achieved by transmitting at higher effective power (for both down-link and up-link channels); installing base stations at higher altitude above ground level and using lower radio frequency decrease propagation loss and improve coverage. For the same propagation reason, lower frequencies are preferred for rapid roll-out, as less cellular base stations are needed. But, the available RF bandwidth is reduced at lower RF; for example, compare the FDD: GSM/UMTS 900 MHz band (39x2 MHz\(^{55}\)), versus the UMTS 2,100 MHz band (60x2 MHz\(^{56}\)). Furthermore, due to extended propagation loss, higher frequencies decrease interference from neighbouring sites, to enable installation of more base stations and enhance capacity. The idea of cellular is to get more capacity not by more RF spectrum, but rather by more sites; so, additional sites solve traffic and throughput problems. Grace D. et al. 2009 do emphasise in green radio the direct trade-off between bandwidth and power (energy) efficiency ‘we should strive to maximize the bandwidth usage, if we wish to minimize power usage (energy resources)’. Only the most loaded sites need extra capacity\(^{57}\). In urban areas the limiting factor is the system capacity, while the coverage problems are dominant in rural areas. The major part of the system cost resides in the core of the system, where the limiting factor is capacity; this implies that in urban areas the major design factor is frequency reuse based on capacity determinant signal to interference (S/I), rather than on signal to noise (S/N), for coverage\(^{58}\).

Higher data rates oblige more RF spectrum, reduce the range achievable by the base station (WHO 2007 p.25-6 and155) and enforce in urban areas denser base stations. An alternative solution to the capacity problem and additional cellular sites in urban areas is supplementary RF spectrum for the cellular operators. However, around the world, the RF Spectrum of cellular systems is the scarcest, only comparable to the 87.5–108 MHz, FM radio broadcasting, known as Band II internationally. As additional spectrum, sharing (network, planning, base stations and RF spectrum) also reduces the number of sites and human-hazards; more active sharing (including shared RF) saves spectrum and hazards, but may decrease competition; see paragraph 2.3.3.1.

The data explosion\(^{59}\) in the cellular demand requires supplementary cellular infrastructure in industrial, commercial and dense urban zones to accommodate traffic increase; therefore more RF radiation and human exposure. Additional base stations and RF spectrum contribute more

\(^{54}\) Due to the large numbers, India provides good statistics. according the data of the Ministry of Communications and Information Technology, Department of Telecommunications (DoT), on 31st March 2013 service area wise in India, the number of wireless subscribers was 867,803,583 and the number of base stations was 746,602: 0.86 pro mil; see also India TRAI 2013 pp. 1.10 and 13; on 30 June 2013 service area wise in India, the number of wireless subscribers was 873,362,533.

\(^{55}\) RF band 876-915 MHz up-link and 921-960 MHz down-link, including the GSM-R and extended GSM bands.

\(^{56}\) RF band 1,920-1,980 MHz up-link, 2,110-2,170 MHz down-link; in addition UMTS TDD operates at 1,900-1,920 and 2,010-2,030 MHz.

\(^{57}\) The dense-urban sites are separated about 300 meters, while rural are distanced more than 900 meters apart; see Report ITU-R M.2290 table A.7 ‘assumed cell area per radio environment’. When data defines the traffic, as a rule of thumb: about 80% of sites carry 20% of traffic, and 50% of sites carry 5% of traffic.

\(^{58}\) The urban cellular system is interference-limited, not noise limited, and it operates at the minimum signal-to-interference-plus-noise ratio (SINR) or signal-to-noise-plus-interference ratio (SNIR) possible for a given quality. The base stations are built for a well contained coverage, not for maximal coverage, because overlap involves interference.

\(^{59}\) In this evolving era of data services, there is a marked difference in the way the user holds the handheld. In cellular conversation the person may hold the handset tightly against one ear such that it is in tight proximity to the brain. With data, one holds the mobile device in his hands or knees, which is a different hazards environment, probably more benign.
capacity and increase human exposure\(^6^0\). The U.S. adopts liberal policies to facilitate wireless infrastructure deployment and collocations; see FCC Report and Order 14-153 Wireless Infrastructure.

### 9.6.3 Trial to Quantify RF versus Sites

#### 9.6.3.1 Theory

The cellular signals are fading channels. Based on Shannon theorem and on the information theory of fading channels, Biglieri E., Proakis J. and Shamai (Shitz) S. October 1998 emphasize capacity, as the most important performance measure. Intuitively, it is clear that more RF reduces the number of sites; in order to quantify the relation between the site numbers and the RF spectrum, numerical simulations for different scenarios (including propagation analysis of obstacles and fading) are needed. Such quantitative analysis might be performed using the simulation framework developed for heterogeneous networks; see Tsalolikhin et al. 2012. The statistical models of fading channels, to analyse cellular networks, are beyond the scope of this chapter.

The maximum channel capacity for each communications link in a given network is derived from Shannon Hartley monumental paper (Shannon 1948 p. 43, theorem 17), relating capacity (bit/s), RF bandwidth (Hz) and the signal to noise (dimensionless) ratio:

\[
c = b \times \log_2 \left(1 + \frac{s}{n}\right)
\]

(9.17)

The Shannon equation (9.17) is a fundamental theoretical as well as practical tool; it shows a trade-off between bandwidth \(b\) and power \(s\): the capacity increases linearly with the increase bandwidth \(b\), but only logarithmically with the increase in power \(s\) (Grace D et al. 2009). Two significant works in Scott, Pogorel and Pujol employ Shannon Hartley trade-off. Carter (2013 pp.41-62) apply trade-offs between permissible signal strength and allotted channel widths; Yuguchi (2013 pp. 63-76) emphasises the trade-off between investing in better equipment (in order to effectively improve the signal-to-noise ratio) versus investing in more or better spectrum.

#### 9.6.3.2 Quantification: RF versus Sites

The following analysis to quantify that additional RF reduces the number of cellular sites is simplistic; as Shannon capacity equation relates mainly to a fixed Gaussian channel, but the mobile radio link is a faded link\(^6^1\). The first part of (9.17) links the channel capacity \(c\) and the assigned RF Spectrum \(b\); \(c\) depends directly on \(b\); but the noise \(n\) also depends on of the basic RF bandwidth \(b\) as \(n = n_0 \times b\); where \(n_0\) denotes the noise spectral density; noise power per Hz; energy in Joule units.

Firstly, the maximum capacity of the channel is calculated

\[
c = b \times \log_2 \left(1 + \frac{s}{n_0 \times b}\right) = \frac{1}{\ln 2} b \times \ln \left(1 + \frac{s}{n_0 \times b}\right)
\]

; given \(b\) is very large, and \(n_0 \times b \gg s\), using Taylor series, the ultimate data rate Shannon limit equals:

---

\(^6^0\) Expanding the supply (coverage and capacity) also increases the demand of cellular broadband services. Do all video applications justify the cost of additional RF human exposure from base stations and handsets?

\(^6^1\) The Shannon equation refers to a white noise and to an unlimited code and symbol length; data application that dominates the advanced cellular generations may have different optimization rules. However, when many neighbours interfere, the law of large numbers applies (not the case of one dominant interferer), and the noise assumption is Additive White Gaussian Noise (AWGN).
Radio Spectrum Management: Policies, Regulations, Standards and Techniques

Limitations to Radio Frequency Human Exposure

\[
c = \frac{1}{\ln 2} b \times \left( \frac{s}{n_b} - \frac{1}{2} \left( \frac{s}{n_b} \right)^2 + \frac{1}{3} \left( \frac{s}{n_b} \right)^3 - \frac{1}{4} \left( \frac{s}{n_b} \right)^4 + \ldots \right) \approx \frac{1}{\ln 2} \left( \frac{s}{n_b} \right)
\] (9.18)

For the case of very large \(b\), equation (9.18) reveals that the capacity \(c\) is limited by power \(s\) and noise density \(n_o\).

At the log\(_2\) part of equation (9.17), decreasing the number of sites reduces the overall signal at the corresponding locations, as the distances to the base stations increase\(^6^2\). Therefore, staying with the same capacity- less sites (reduced \(s\)) can be compensated by more frequency band \((b)\). It is possible to aim to the Shannon Hartley capacity limit, by adding RF spectrum \((b)\) and decreasing number of sites \((s/n)\): \(b\) is increased and \(s/n\) is reduced (the opposite is also true- more sites, less RF spectrum); thus, without harming the network’s maximum capacity \((c)\) and quality of service. Moreover, in urban scenario \(s/n\) is small. The LTE reference signal received quality (RSRQ) quantifies the capacity; the user equipment UE measures this parameter as reference signal. Values higher than \(-9\text{dB}\) guarantee the best subscriber experience; the range between \(-9\) and \(-12\text{dB}\) can be seen as neutral with a slight degradation of quality of service; see in chapter 2 paragraph 2.3.3.2.2 Capacity.

So for small \(s/n\) relative to 1, using again Taylor series, equation (9.17) aims to:

\[
c = b \times \log_2 \left(1 + \frac{s}{n} \right) = \frac{b}{\ln 2} \ln \left(1 + \frac{s}{n} \right) \approx \frac{b}{\ln 2} \frac{s}{n} \approx 1.44 \times b \times \left(\frac{s}{n}\right)
\] (9.19)

In this case decreasing \(s/n\) (less sites) is compensated directly by increasing \(b\).

Important to note that increasing the channel bandwidth \(b\) and decreasing the \(s/n\) will not necessarily reduce power at down-link and up-link signals and human exposure from specific base station and handset; as the increase of RF spectrum may oblige increase in power, to preserve power per Hz. In all cases, adding cellular sites increases coverage and capacity, and decreases the RF exposure from (specific base station and) handsets. However, people still dislike cellular masts near them.

Summary, cellular capacity is limited by RF bandwidth, power and noise; adding RF to base stations may decrease the number of base stations and the total EMF.

9.7 Policies and mitigation techniques to reduce the human exposure

9.7.1 Policies to reduce the human exposure to RF radiation

Derived from the precautionary-principle, these are polices to reduce human hazards:

- Follow the existing ICNIRP 1998 limits from stations and cellular handsets at the national level and across the country. These exposure limits are the current international scientific consensus. The tolerability of the human body to RF radiation is independent of geography or political borders; there is no technical justification for different national exposure levels. Cellular networks are not local; there is no engineering reason for different exposure levels among cities inside the country; the definition of exposure limits should be national\(^6^3\), and outside the competency of municipal or provincial councils;
- Follow the council of Europe, Resolution 1815 (2011) considering §5 and recommendation § 8.5.4, apply the:

\(^6^2\) Noise \(n\) is also dependent of the sites’ density; in urban area, \(n\) is dominated by neighbour cell interference, not thermal noise.

\(^6^3\) The ‘Salzburg model’ seems not to have been effective under any point of view. It has prevented the development of networks, with no evident health benefit for public health; at the same time, it has not settled down the controversies and probably has not reduced public concern (WHO 2007 p.148).
ALARA (as low as reasonably achievable) principle, covering both the so-called thermal effects and the a-thermic or biological effects of electromagnetic emissions or radiation; see also recommendations § 8.1.2 and 8.4.3; and

The precautionary-principle, when scientific evaluation does not allow the risk to be determined with sufficient certainty. Given the context of growing exposure of the population, in particular that of vulnerable groups such as young people and children, there could be extremely high human and economic costs if early warnings are neglected; see also recommendation § 8.2.1;

Follow the council of Europe, Resolution 1815 recommendation § 8.2.3: introduce clear labelling indicating the presence of microwaves or electromagnetic fields, the transmitting power or the SAR of the device and any health risks connected with its use;

Prioritize the alternative cable and satellite telecommunications, in order to reduce off-air TV, fixed wireless access emissions, wireless internet router and broadband applications;

Promote cellular sites’ co-location passive (same site, mast and antenna) and even active sharing (same transceivers and frequencies) among operators, in order to reduce the number of the cellular base stations and in general the human exposure;

Do not limit construction of masts near sensitive places, as the individual exposure from the handsets increases, with fewer base station antenna, due to handset power growth65.

Inform the public transparently about existing and expected exposure values, by performing simulations. For the cell phones: provide good visible publication of the SAR values;

Theoretically assess every base station to assure that general public exposure is lower than ICNIRP 1998 reference levels; measure upon request; try to software monitor the exposure and emitted power 24 hour a day 365 days a year; and

Solve the property devaluation problem.

9.7.2 Mitigation techniques to decrease the radiation level

Enclosed techniques to reduce the human exposure:

Restrict access to areas where the exposure limits are exceeded. Physical barriers, lockout procedures and adequate signs are essential; workers can use protective clothing (Recommendation ITU-T K.52);

Increase the antenna height. The distances to all points of investigation are increased and the radiation level is reduced. Moreover, additional attenuation to the radiation is achieved due to the increase of off-boresight elevation angle and decrease of transmitting antenna sidelobe (K.70);

Increase the antenna gain (mainly by reducing the elevation beam width), and consequently decrease the radiation in the direction accessible to people. The vertical beam width may be used to reduce the radiation level in close proximity to the antenna. Moreover, the same value of the eirp can be achieved by a low power transmitter feeding high gain antenna or by high power transmitter feeding low gain antenna. As far as the protection against radiation is concerned, a much better choice is to use the low power transmitter feeding the high gain antenna. (K.70); and

Minimize the base station transmission to the minimum needed to maintain the quality of the service, as quality criterion. Decrease the transmitter power and consequently decrease linearly the power-density in all the observation points. As this mitigation technique reduces the coverage area, it is used only if other methods cannot be applied (K.70).

---

64 Co-location increases human exposure near the specific site; but the general public exposure is reduced.

65 Regards minimum distances from buildings and inhabited areas ‘Contrary to the general perception of the public, such measures increase, rather than decrease, the average environmental level of EMF’ (WHO 2007 p.148).
9.7.3 Myths and Realities

The public hypersensitivity and electrophobia lead to some myths which are contrary to physical realities. The following is a summary of these situations:

- **Myth:** the construction of a site antenna in one’s neighborhood should be of RF human exposure concern to people of that neighborhood.
- **Reality:** quite the opposite. As use of handsets is total, the limiting factor in terms of EMF exposure is the transmissions from the handset (up-link). This is the case in view of its physical proximity to the user’s body. The handset transmissions are power controlled, such that the handset does not transmit higher power than what is necessary to maintain reliable communications. Closer to the site the handset transmits less power;
- **Myth:** the higher the number of the transmitting sites in a given area the higher the EMF exposure.
- **Reality:** not true. In reference to the exposure from the handset see the above; due to the profusion of sites, the handsets are closer to their corresponding base station and emit less. For radiation from the site antenna, the transmission levels are such that they should allow quality of service at the cell boundaries. The power-density attenuates as the square of distance in free space and with a higher exponent (typically around 4 for ground waves) resulting in higher levels at the inner areas of the cell. The smaller the cells the smaller is that extra exposure levels in the inner parts of the cell;
- **Myth:** the larger the dimensions of the cell site and antennas, the higher the exposure.
- **Reality:** not true. Antennas are made big in order to get higher gains of main beams. As a result the field-strength (and power-density) in the area close to the antenna is reduced; it is achieved due to the sidelobe in elevation; and
- **Myth:** an antenna erected on the roof causes maximum exposure inside the building underneath.
- **Reality:** not true. The antenna transmits horizontally (or some small downtilt) such that directly underneath, the transmissions are much reduced. Moreover, a concrete roof is a quite strong attenuator of EMF.

9.8 Conclusions

The global regulations and guidelines of occupational exposure limits are continuously reviewed by experts. The summary of IARC 2013 p.409 ‘it is likely that not all mechanisms of interaction between weak RF fields, with the various signal modulations used in wireless communications, and biological structures have yet been discovered or fully characterized’.

The national limitations to radio frequency human exposure are becoming more stringent, due to societal concerns and electromagnetic hypersensitivity. Municipalities and national administrations strive to lower thresholds. Worldwide standards and universal thresholds on human-hazards will avoid a Babylon tower of standards that confuse suppliers, operators and users. The globalization and harmonization may lead to the adoption of the universal levels of ICNIRP 1998. Furthermore, there is no technical justification for different exposure levels. The underlining factor of the RF exposure of humans is the subscriber’s handset and not the base antenna. Wireless communications are vital. Due to the high number of people exposed to RF radiation, while scientific uncertainty on harmful effects still exists, implementing the precautionary-principle is warranted and reasonable; efforts are needed to reduce the human exposure to RF, as low as reasonably achievable.
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