WHITE PAPER

EMF Radiation in Mobile Networks: A Closer Look at Emission Limits & Safe Distances

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TABLE OF CONTENTS

1 INTRODUCTION

An Electromagnetic Field (EMF) Radiation is an area of moving Electrical and Magnetic (EM) Field through a medium. A medium is usually air, although EM can propagate in other mediums such as water or vacuum. The movement of EMF is a byproduct of electrical current; wherever there is electric current, there must be EMF radiation in its vicinity. EMF is sometimes an unwanted byproduct of a current, as is the case with high voltage power lines. However, in wireless networks, EM field is the desired product, as the EM field carries the information from an antenna to mobile phones and laptops and vice versa. Over the years, questions arose whether EMF radiation coming from mobile wireless networks is harmful to humans. Various government and non-government agencies have tackled this problem in the past and defined what constitutes an acceptable EMF emission.

Recently, as 5G technology started to get deployed at millimeter wave frequencies, a public debate arose whether a 5G network EMF radiation is harmful to unsuspecting general population. This white paper summarizes the emission limits imposed by various worldwide governing bodies, gives theoretical background regarding the computation of EMF radiation compliance distance, and gives numerical examples as to what the safe distance from emission is in indoor wireless networks in selected countries around the world. We also discuss how adding a new 5G network to an existing in-building multi-technology (2G, 3G, 4G) network affects the compliance distance. We also discuss how massive MIMO technology, which is an important part of 5G networks, impacts the compliance distance, with numerical examples generated by iBwave Design, a commercial indoor RF design and planning tool.

2 EMF RADIATION LIMITS AROUND THE WORLD

2.1 ICNIRP GUIDELINES

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides scientific advice and guidance on the health and environmental effects of non-ionizing radiation (NIR) to protect people and the environment from detrimental NIR exposure. Non-ionizing radiation is Electromagnetic Field radiation in the 100 kHz – 300 GHz range.

ICNIRP gives recommendations on limiting exposure for the frequencies in the different NIR subgroups. It develops and publishes Guidelines, Statements, and reviews used by regional, national, and international radiation protection bodies, such as the World Health Organization. ICNIRP is a main contributor to the international scientific NIR dialogue and the advancement of NIR protection.[1].

The ICNIRP limits are based on an extensive review of the scientific literature to identify potentially hazardous effects and their thresholds. The potentially harmful biological effects are based on the disruption of ongoing behaviors associated with an increase of body temperature on the presence of electromagnetic fields. Because of the lack of reliable data on chronic exposures, most of the literature concerned short-term (less than an hour) exposure to RF energy. The averaging times in the ICNIRP limits are short (6 – 30 minutes) and reflect thermal considerations.

ICNIRP gives exposure limits using a variety of metrics over a wide range of frequencies. One such metric is “Specific energy absorption rate” (SAR), which is the power per absorbed unit mass (W/kg). This is a useful metric to use below 6 GHz, where EMF penetrate deep into tissue. Above 6 GHz EMF is absorbed more superficially, so it is useful to describe exposure in terms of density of absorbed power over area (W/m^2). This metric is colloquially called “power density”. Power density is exclusive metric above 10 GHz [1, Table 5], while SAR is specified below 10 GHz [1, Table 4], for whole body, limb and head. ICNIRP also specifies incident electric and magnetic field and power density below 10 GHz, where “calculated reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded” [1].

The ICNIRP sets two different exposure limits:

- Occupational exposure limits
- General public limits

Occupational exposure limits apply to adult individuals exposed under controlled conditions associated with their occupational duties. They are trained to be aware of potential radiofrequency EMF risks, and how to employ appropriate harm-mitigation measures.

The general public limits apply to individuals of all ages who may have not have knowledge of, or cannot control, their exposure to EMFs. The differences between the groups suggest the need to include more stringent restrictions for the general public, as members of the general public are not trained to mitigate harm or may not have the capacity to do so. Occupationally exposed individuals are not at greater risk than the general public, providing that appropriate screening and training is provided to account for all known risks. [2]

The reference values for electric and magnetic field and incident power density as a function of frequency range are shown in Table 1:

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

Table 1: ICNIRP Reference values, for exposure, averaged over the whole body for EM field in the range 100 kHz – 300 GHz [ibid, Table 5].

Mobile networks operate in the 150 MHz – 40 GHz range. This corresponds to the three frequency ranges in the table above: 30 – 400 MHz, 400 MHz – 2 GHz and 2-300 GHz.

Incident power density S_{inc} is listed in all three frequency ranges of interest, and we will use Sinc to calculate the safe distance from EMF field radiated by an antenna. The safe distance is the distance at which power density S_{inc} is equal to published values in Table 1. This is also called EMF "compliance distance". Getting any closer to than the compliance distance may expose a human to harmful EMF radiation from an antenna.

Based on the values in Table 1, we present S_{inc} variation with frequency in the 150 MHz – 40 GHz range:

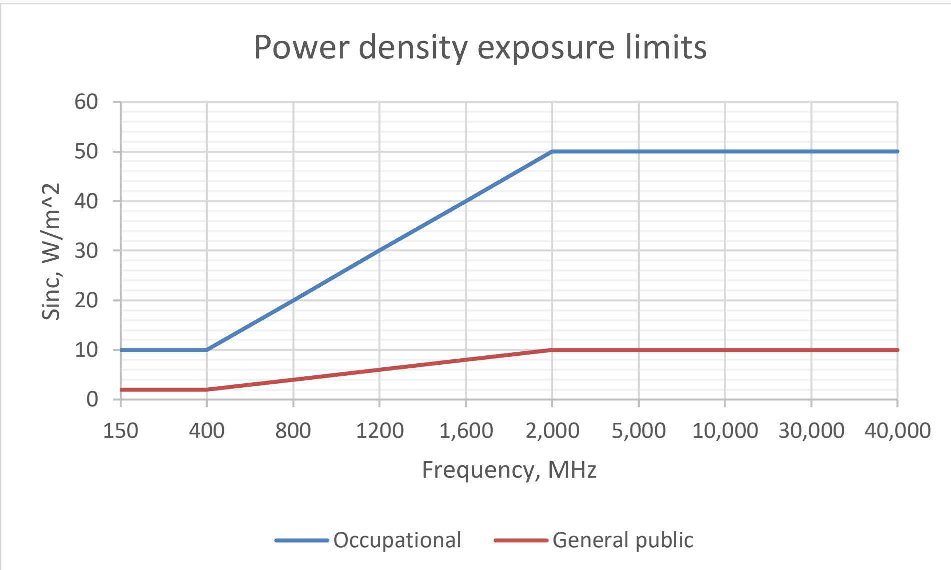


Figure 1: ICNIRP Power density EMF exposure limits for Occupational and General Public.

The occupational EMF exposure limit is 5 times the General public exposure limit. Occupational limits are higher because occupationally exposed individuals are exposed to EMF radiation under controlled conditions associated with their occupational duties and are trained to be aware of potential radiofrequency EMF risks and to employ appropriate harm-mitigation measures.

While ICNIRP gives recommendation exposure limits, it does not have the power to impose them upon local governments. Local governments decide on their own whether to accept the recommendation or come up with their own exposure limits.

2.2 LOCAL GOVERNMENT EXPOSURE LIMITS

Worldwide EMF exposure limits can be identified as three distinct groups. The first group enforces EMF radiation limits based on ICNIRP (or similar, IEEE c.95-1999) recommendations, with or without slight modification. The countries that belong to the first group are USA, Canada, and most Western European countries.

The second group enforces EMF radiation limits based on scientific papers from China and Russia that employ a different methodology than the science papers considered by ICNIRP. These limits are within a few percent of ICNIRP limits, and thus impose much stricter radiation limits. The countries that belong to the second group are Russia, China, India, and some Eastern European countries. Unlike ICNIRP limits, these limits are not designed to protect against increase of body temperature during short term EMF exposure. Rather, they come from the point of view that long-term low-level exposure to RF energy causes headaches, fatigability, irritability, sleep disorder and dizziness. The actual exposure limits in Russian Federation are said to be taken from a study of effects of 3-hour low-level daily RF exposure to experimental animals [3].

The third group enforces precautionary low EMF radiation limits near schools, playgrounds, day care centers and retirement homes, as the occupants are considered the most vulnerable to EMF radiation. This group enforces EMF threshold levels similar to ICNIRP radiation limits in other areas accessible to general population. Switzerland, Italy, and Croatia are among those countries.

EMF radiation power density limit (W/m^2) for all 3 groups is listed in Table 2 [4], [5], [6]. Only the lowest limit is listed, even if applicable only to some areas, such as nursing homes or kindergartens.

Country	**900 MHz**	**1800 MHz**	**2100 MHz**
ICNIRP	4.5	9	10
Austria	4.5	9	10
Bulgaria	0.1	0.1	0.1
Croatia	0.72	1.4	1.7
Cyprus	4.5	9	10
Czech Republic	4.5	9	10
Estonia	4.5	9	10
Finland	4.5	9	10
France	4.5	9	10
Germany	4.5	9	10
Greece	2.7	5.4	6
Hungary	4.5	9	10
Ireland	4.5	9	10
Italy	0.1	0.1	0.1
Lithuania	0.45	0.9	1
Luxemburg	4.5	9	10
Malta	4.5	9	10
Poland	0.1	0.1	0.1
Portugal	4.5	9	10
Romania	4.5	9	10
Slovakia	4.5	9	10
Slovenia	0.45	0.9	1
Spain	4.5	9	10
Sweden	4.5	9	10
United Kingdom	4.5	9	10
Australia	4.5	9	10
China	0.4	0.4	0.4
India	0.45	0.9	1.1
Japan	6	10	10
Russia	0.1	0.1	0.1
Switzerland	0.045	0.095	0.095
USA	6	10	10

Table 2: General public EMF power density (S_{inc}) radiation limits in W/m^2, listed for EU and selected non-EU industrial nations [4], [5], [6].

From Table 2 we see that power density radiation limit S_{inc} varies a lot across the world. Therefore, there is little hope that worldwide EMF radiation harmonization can be achieved soon. It is important to note that according to INCIRP guidelines (Table 1), radiation limit does not change above 2 GHz. Thus, 5G millimeter wave mobile networks are not inherently more dangerous to human health than the existing 4G networks operating at 2.1, 2.6 or 3.5 GHz.

3 EMF RADIATION AND EMF COMPLIANCE CALCULATION

3.1 POINT SOURCE ANTENNAS

Most radiation sources in mobile networks are large panel antennas (outdoor) and small indoor omnidirectional and directional antennas. These are point source radiators, whose electric field decays as ~ 1/d in the far field, where d is the distance of observation point from the center of antenna. Electric field at the receiver E is the summation of direct electric field Ed which travels the distance d between the transmitter and the receiver, and N reflected fields Er which travel the distance Ri between the transmitter and the receiver. Using polar coordinates, we can write the resulting electric field E as:

$$E(d) = E_{direct} + \sum E_{reflected} \sim E_0 \left(G(\theta, \emptyset) \frac{e^{-jkd}}{d} + \sum_{i=1}^{N} \Gamma_i(\theta) G_i(\theta, \varphi) \frac{e^{-jkR_i}}{R_i} \right) \quad (1)$$

Where E_0 is electric field amplitude at antenna input, $G(\theta,\alpha)$ is antenna gain and Γ (θ) is reflection coefficient of the reflected surface. The direct and reflected electric fields can be calculated using RF design and planning tool that employs Ray Tracing, such as iBwave Design.

Power density S at the distance d from antenna can be expressed as:

$$S = \frac{|E(d)|^2}{Z_o} = \frac{E_o^2}{Z_o} \left| G(\theta, \alpha) \frac{e^{-jkd}}{d} + \sum_{i=1}^{N} \Gamma_i(\theta) G_i(\theta, \alpha) \frac{e^{-jkR_i}}{R_i} \right|^2 \quad (2)$$

Where Z_0 is free space impedance. In terms of power P_0 at antenna port, power density S is:

$$S = \frac{P_o}{4\pi} \left| G(\theta, \alpha) \frac{e^{-jkd}}{d} + \sum_{i=1}^{N} \Gamma_i(\theta) G_i(\theta, \alpha) \frac{e^{-jkR_i}}{R_i} \right|^2 \quad (3)$$

Antenna gain G is three dimensional, and for directional antennas its peak is along direction perpendicular to antenna panel. This direction perpendicular to antenna panel is also called antenna broadside, shown along the yellow line in Figure 2.

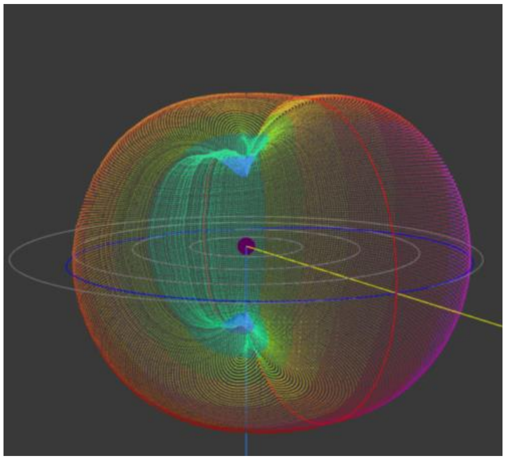


Figure 2: Three-dimensional directional antenna pattern, with antenna broadside along the yellow line

Antenna gain varies in space, and in polar coordinates this variation is a function of horizontal angle α and vertical angle θ. The maximum gain, which is always listed in antenna spec sheet, is in the broadside direction, where $\alpha = 0^o$ and $\theta = 0^o$. Two-dimensional antenna patterns called vertical ($\alpha = 0^o$) and horizontal ($\theta = 0^o$) antenna patterns (or "cuts") are also listed in antenna spec sheets, as illustrated in Figure 3.

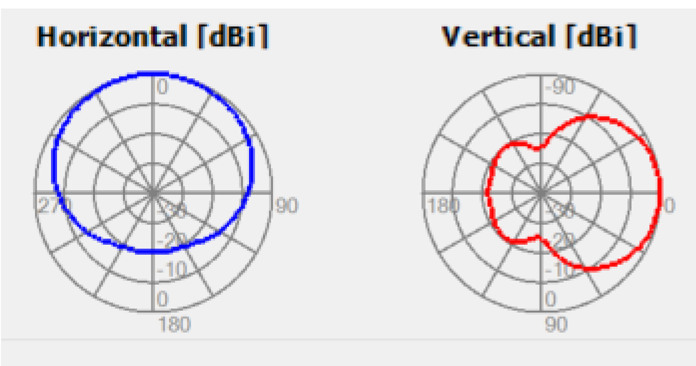


Figure 3: Two dimensional horizontal and vertical antenna patterns taken from 3-dimensional antenna pattern in Figure 2.

Far field EMF compliance distance is a distance d, as per equation (3), at which the power density S is equal to EMF Radiation limit S_{inc}. As S is a function of antenna gain G and reflection coefficient Γ, the distance d is not a constant, but a function of polar coordinates α and θ. The maximum EMF radiation compliance distance d_{max} is in the direction of the maximum antenna gain, G = Ag. For a very conservative EMF Radiation compliance, we can assume that EMF Radiation Compliance is d_{max} in all directions from antenna. This assumption works well for indoor omnidirectional antennas because they radiate similar amount of EM radiation in all directions. However, the assumption breaks down for highly directive antenna arrays, such as m-MIMO, which will be addressed later in this paper.

3.2 MULTI-BAND NETWORKS

In multi-band wireless networks, we need to calculate the compliance distance when transmit antennas for multiple bands are collocated and all networks transmitting at different spectrum bands are active. This is usually the case when a network supports multiple technologies: GSM, HSPA, LTE and 5G NR. To do this, we introduce a new parameter, R_f, which is a ratio of measured power density at a distance d and at frequency f, versus exposure limit Sinc at frequency f:

$$R_f = \frac{Calculated\ S\ distance\ d\ and\ frequency\ f}{Exposure\ limit\ S_{inc}\ at\ frequency\ f} \tag{4}$$

R_f is calculated separately at each active frequency in the network. If the network has 5 different bands, for example 700, 850, 1900 MHz and 3.5 and 28 GHz, there will be five R_f values to compute. The goal is to find EMF radiation compliance distance d at which the summation of all five R_f values is equal to 1.

$$\sum_{i=1}^{5} R_f = 1 \tag{5}$$

This is an iterative process, which can be best described as finding a root of function f(x)=0. First, choose a distance d_0 as a starting point, calculate R_f at each frequency using the distance d_0, sum all R_f up, and check if the summation is equal to 1, within certain tolerance. If it is not, then the new distance d_1 is $2d_0$ if the summation is less than one, and if it is greater than 1 then $d_1=d_0/2$. The next step is to recalculate R_f at each frequency and check if the summation is equal to 1. The process is repeated until we find a distance d for which the summation is equal to 1, within certain tolerance.

3.3 HOW SPECTRUM AND TECHNOLOGY AFFECTS EMF COMPLIANCE DISTANCE

EMF radiation compliance distance is a function of input power, antenna gain, reflection from surface and power density. According to [2], incident power density S must be averaged over time, and thus all parameters that contribute to S must be averaged as well. This must be done if:

- Spectrum is shared between uplink and downlink (TDD systems)
- Input power fluctuates due to variation in cell load at eNodeB in real time (3G, 4G, 5G)
- Antenna pattern fluctuates in real time (Massive MIMO)

3.3.1 TDD SYSTEMS

When uplink and downlink share spectrum, input power must be averaged over time to account for the time when downlink does not transmit. The DL transmission duration as a fraction of the overall transmission duration needs to be known. Then, the average power $\overline{P_o}$ as a function of the nominal power P_0 is:

$$\overline{P_0} = P_O \frac{T_{DL}}{T_{FRAME}} \tag{9}$$

Where Po is nominal amplifier power in Watts, T_{DL} is downlink transmission duration within a frame, and T_{FRAME} is frame duration.

3.3.2 eNodeB CELL LOAD

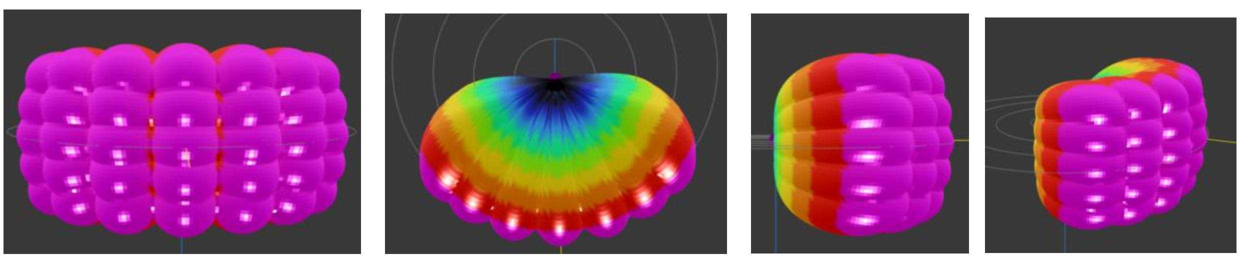
An eNodeB transmit power fluctuates with the number of UEs transmitting/receiving the signal. The ratio of the number of active UEs vs. the theoretical maximum number of active UEs is called eNodeB “cell load”. Operators usually design their networks to support average cell load in the 50-70% range during busy hour. Another important parameter is overhead, which is a fraction of the transmit power reserved for signaling. For LTE, it is in the 10-30% range, while for 5G NR it is in the 14-18% range. The average power $\overline{P_o}$ as a function of the nominal power P_0 is:

$$\overline{\boldsymbol{P_0}} = \boldsymbol{P_O} * (OH + (1 - OH) * CL) \quad (10)$$

Where OH is overhead in percentage, CL is cell load in percentage, and P_0 is nominal amplifier power in Watts.

3.3.3 MASSIVE MIMO

Massive MIMO (m-MIMO) antennas are two-dimensional beamforming antenna arrays that form a high gain narrow beam antenna pattern in direction of a user. Some m-MIMO antennas are static, which means that each generated beam covers a fixed area of a 120º sector. Some are dynamic, which means that a beam is tracking a user in real time as it moves around within a sector. Figure 5 shows how a static m-MIMO antenna pattern with 35 beams would look like if all beams were to transmit a signal at the same time.



(a) (b) (c) (d)

Figure 5: (a) broadside (b) horizontal cut (c) vertical cut (d) side view of static m-MIMO antenna pattern, all beams active

A formula to calculate individual m-MIMO beam gain is $G_{m\text{-}MIMO} = G_{antenna} + 10\log10(N\_array)$, where $G_{antenna}$ is the gain of individual antenna in the array, and N_array is the number of antennas. If $G_{antenna}$ = 0 dBi and N_array = 64, then $G_{m\text{-}MIMO}$ = 18 dBi.

EIRP is Equivalent Isotropic Radiated Power, and is a product of input power P_0 and antenna gain G. In the context of m-MIMO, EIRP is defined per beam, so in the above example with 35 beams we would have 35 EIRPs. However, those EIRPs are not constant in time, because it is not prudent to have all m-MIMO beams transmit at the same time, as this would degrade SINR and reduce throughput at UE. Only a few m-MIMO beams are active at any given time, and the decision which beams to activate and which to turn off is made in real time, with a goal to reduce interference. Thus, m-MIMO radiation pattern changes in real time, and the constant switching of beams on and off means that EIRP per beam must be averaged out.

According to [7], average EIRP power in Watts per m-MIMO beam is only 25% of the instantaneous EIRP. This reference claims that the 25% value is a conservative estimate, and also considers a typical DL/UL split in a TDD network. In the above example, if power into antenna is 20 dBm and 64 array m-MIMO gain per beam is 18 dBi, instantaneous EIRP per beam is 38 dBm. Reduction of EIRP transmission in Watts from 100% to 25% corresponds to 6 dB reduction in power in logarithmic scale, so average EIRP per beam is 38 – 6 = 32 dBm.

3.4 EMF COMPLIANCE CALCULATION EXAMPLES – INDOOR NETWORKS

3.4.1 USA

As per Table 2, USA has the highest power density emission limits among the listed nations. Thus, we expect the compliance distance to be shorter in USA than in any other country listed in the table. An example of EMF compliance distance calculation across 5 frequency bands in the USA (700, 850, 1900 MHz and 3.5 and 28 GHz), and with FCC mandated radiation limits [6] is shown in Figure 6, per EMF Radiation report generated by iBwave Design.

Antenna ID	System ID	Composite power		Power density
		Before ant. (dBm)	After ant. (EiRP) (dBm)	(W/Sq. m)
TCVR1	System1	23.01	23.01	10.0000
TCVR1	System2	23.01	35.01	10.0000
TCVR1	System3	23.01	23.01	4.9733
TCVR1	System4	20.00	20.00	5.9600
TCVR1	System5	23.01	23.01	10.0000

EMF statistics (safety distance)						
System ID	Average (cm)	Std. dev. (cm)	Minimum		Maximum	
			Antenna ID	(cm)	Antenna ID	(cm)
System1	3.99	-	TCVR1	3.99	TCVR1	3.99
System2	15.88	-	TCVR1	15.88	TCVR1	15.88
System3	5.66	-	TCVR1	5.66	TCVR1	5.66
System4	3.65	-	TCVR1	3.65	TCVR1	3.65
System5	3.99	-	TCVR1	3.99	TCVR1	3.99

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 400 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 700 MHz / FDD - 10 MHz - Band 12 / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 850 MHz - Cellular / ALL / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 1900 MHz - PCS / All 5 MHz / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1

Figure 6: EMF compliance report for a multi-technology multi-band indoor wireless system (USA market).

GSM (System 4) is a SISO system. HSPA+, LTE and 5G NR are 2x2 MIMO systems. 5G NR at 28 GHz (System 2) is a cross polarized m-MIMO (8x8x2 panel).

While all power amplifiers transmit 20 dBm into antenna ports, 2x2 MIMO systems have two amplifiers, each feeding one cross polarized antenna. For EMF radiation compliance calculation, we can approximate the two amplifiers as a single amplifier transmitting at double the power (23 dBm). Therefore, all systems, except for GSM (System 4) list 23 dBm as input power.

All antennas are omnidirectional 0 dBi antennas, except for m-MIMO at 28 GHz, which has 18 dBi gain per beam. A 6 dB m-MIMO gain reduction is applied System 2 EIRP, as explained in Section 3.3.3.

Figure 6 lists compliance distances for each individual technology/band. However, we need to calculate the compliance distance when all technologies/bands are active. Using the algorithm outlined in Section 3.2, we get the following result, as per EMF radiation compliance report generated by iBwave Design:

Antenna ID	System ID	Composite power		Power density
		Before ant. (dBm)	After ant. (EiRP) (dBm)	(W/Sq. m)
TCVR1	System1	23.01	23.01	0.4831
TCVR1	System2	23.01	35.01	7.6571
TCVR1	System3	23.01	23.01	0.4831
TCVR1	System4	20.00	20.00	0.2416
TCVR1	System5	23.01	23.01	0.4831
TCVR1	All systems	29.54	35.88	9.3480

EMF statistics (safety distance)						
System ID	Average (cm)	Std. dev. (cm)	Minimum		Maximum	
			Antenna ID	(cm)	Antenna ID	(cm)
System1	18.15	-	TCVR1	18.15	TCVR1	18.15
System2	18.15	-	TCVR1	18.15	TCVR1	18.15
System3	18.15	-	TCVR1	18.15	TCVR1	18.15
System4	18.15	-	TCVR1	18.15	TCVR1	18.15
System5	18.15	-	TCVR1	18.15	TCVR1	18.15

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 400 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 700 MHz / FDD - 10 MHz - Band 12 / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 850 MHz - Cellular / ALL / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 1900 MHz - PCS / All 5 MHz / Sector number:: 2 / Nb. of channels: 1 / Nb. of sources: 1

Figure 7: Composite EMF compliance report when all 5 systems are active (USA market)

The first table in Figure 7 shows power density value for each system at composite compliance distance. The second table shows the actual value of the composite compliance distance, d = 18.15 cm.

An interesting question to answer is how much of an influence m-MIMO has on compliance distance? To answer that question, we calculated compliance distance when only non-5G NR systems are active (GSM, HSPA+, LTE), and then when all systems except for 28 GHz (m-MIMO) are active. We compare the results side by side, in centimeters, in Table 3.

	Non 5G systems only	All systems active except m-MIMO	All systems active, including m-MIMO
Compliance distance, cm	7.8	8.8	18.15

Table 3: Compliance distance, in centimeters, with and without 5G NR networks (USA)

It is clear that m-MIMO 5G NR has significant influence on EMF radiation compliance distance in the USA market. The compliance distance increased by 110% when 28 GHz m-MIMO was added to multi-technology multi-band indoor wireless system.

3.4.2 SLOVENIA

For the second example we choose Slovenia, as its' power density radiation limit S_{inc} is one tenth of the ICNIRP, as per Table 2. The indoor network we choose is similar, except for a few changes in spectrum bands: 900 MHz, 1800 MHz, 2100 MHz, 3.5 GHz and 28 GHz. The technologies are the same: GSM, HSPA+, LTE and 5G NR. GSM technology is SISO. HSPA+, LTE and 5G NR are 2x2 MIMO. At 28 GHz we use polarized m-MIMO with 8x8x2 panel. EMF compliance report generated by iBwave Design for individual systems is shown in Figure 8 below:

Antenna ID	System ID	Composite power Before ant. (dBm)	Composite power After ant. (EiRP) (dBm)	Power density (W/Sq. m)
TCVR1	System1	23.01	23.01	1.0000
TCVR1	System2	23.01	35.01	1.0000
TCVR1	System3	20.00	20.00	0.4500
TCVR1	System4	23.01	23.01	0.9000
TCVR1	System5	23.01	23.01	1.0000

EMF statistics (safety distance)						
System ID	Average (cm)	Std. dev. (cm)	Minimum Antenna ID	Minimum (cm)	Maximum Antenna ID	Maximum (cm)
System1	12.62	-	TCVR1	12.62	TCVR1	12.62
System2	50.22	-	TCVR1	50.22	TCVR1	50.22
System3	13.30	-	TCVR1	13.30	TCVR1	13.30
System4	13.30	-	TCVR1	13.30	TCVR1	13.30
System5	12.62	-	TCVR1	12.62	TCVR1	12.62

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 50 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 900 MHz - GSM / P-GSM900 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 1800 MHz - DCS / FDD - 10 MHz - Band 3 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 2100 MHz - UMTS / HSPA2100 - block I 5 MHz / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1

Figure 8: EMF compliance report for a multi-technology multi-band indoor wireless system (Slovenia).

As was the case in the USA example, 5G NR m-MIMO technology has the greatest compliance distance. EMF compliance report when all systems are active is shown in Figure 9:

Antenna ID	System ID	Composite power Before ant. (dBm)	Composite power After ant. (EiRP) (dBm)	Power density (W/Sq. m)
TCVR1	System1	23.01	23.01	0.0498
TCVR1	System2	23.01	35.01	0.7896
TCVR1	System3	20.00	20.00	0.0249
TCVR1	System4	23.01	23.01	0.0498
TCVR1	System5	23.01	23.01	0.0498
TCVR1	All systems	29.54	35.88	0.9640

EMF statistics (safety distance)						
System ID	Average (cm)	Std. dev. (cm)	Minimum Antenna ID	Minimum (cm)	Maximum Antenna ID	Maximum (cm)
System1	56.52	-	TCVR1	56.52	TCVR1	56.52
System2	56.52	-	TCVR1	56.52	TCVR1	56.52
System3	56.52	-	TCVR1	56.52	TCVR1	56.52
System4	56.52	-	TCVR1	56.52	TCVR1	56.52
System5	56.52	-	TCVR1	56.52	TCVR1	56.52

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 50 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 900 MHz - GSM / P-GSM900 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 1800 MHz - DCS / FDD - 10 MHz - Band 3 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 2100 MHz - UMTS / HSPA2100 - block I 5 MHz / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1

Figure 9: Composite EMF compliance report when all 5 systems are active (Slovenia)

Let's now compare this compliance distance with the compliance distance when only non-5G NR networks are active, and when all networks except m-MIMO 5G NR at 28 GHz are active. The results are shown in Table 4, in centimeters.

	Non 5G systems only	All systems active except m-MIMO	All systems active, including m-MIMO
Compliance distance, cm	22.6	25.9	56.5

Table 4: Compliance distance, in centimeters, with and without 5G NR networks (Slovenia)

As was the case with the USA example, adding an m-MIMO 5G NR system at 28 GHz increased the compliance distance by more than 110%.

3.4.3 RUSSIAN FEDERATION

The last example is a country that has the most restrictive Sinc radiation limit – Russian Federation. According to Table 2, Sinc limit is just 0.1 W/m2 for all frequencies of interest. Thus, we expect EMF radiation compliance limit is going to be the largest in Russian Federation.

To make the comparison between the three countries easier, we use the same multi-technology multi-band system in Russian Federation as the one in Slovenia. EMF compliance report generated by iBwave design for individual systems is shown in Figure 10.

Antenna ID	System ID	Composite power Before ant. (dBm)	Composite power After ant. (EiRP) (dBm)	Power density (W/Sq. m)
TCVR1	System1	23.01	23.01	0.1000
TCVR1	System2	23.01	35.01	0.1000
TCVR1	System3	20.00	20.00	0.1000
TCVR1	System4	23.01	23.01	0.1000
TCVR1	System5	23.01	23.01	0.1000

EMF statistics (safety distance)						
System ID	Average (cm)	Std. dev. (cm)	Minimum Antenna ID	Minimum (cm)	Maximum Antenna ID	Maximum (cm)
System1	39.89	-	TCVR1	39.89	TCVR1	39.89
System2	158.82	-	TCVR1	158.82	TCVR1	158.82
System3	28.21	-	TCVR1	28.21	TCVR1	28.21
System4	39.89	-	TCVR1	39.89	TCVR1	39.89
System5	39.89	-	TCVR1	39.89	TCVR1	39.89

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 50 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 900 MHz - GSM / P-GSM900 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 1800 MHz - DCS / FDD - 10 MHz - Band 3 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 2100 MHz - UMTS / HSPA2100 - block I 5 MHz / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1

Figure 10: EMF compliance report for a multi-technology multi-band indoor wireless system (Russian Federation

Comparing Figure 8 and Figure 10 we see that EMF radiation distance is about 3 times larger in Russian Federation than in Slovenia, for the frequency bands where power density is 10 times lower than in Slovenia. This is expected, as the compliance distance is inverse of square root of power density.

EMF compliance report when all systems are active is shown in Figure 11.

Antenna ID	System ID	Composite power Before ant. (dBm)	Composite power After ant. (EiRP) (dBm)	Power density (W/Sq. m)
TCVR1	System1	23.01	23.01	0.0052
TCVR1	System2	23.01	35.01	0.0819
TCVR1	System3	20.00	20.00	0.0026
TCVR1	System4	23.01	23.01	0.0052
TCVR1	System5	23.01	23.01	0.0052
TCVR1	All systems	29.54	35.88	0.1000

EMF statistics (safety distance)						
System ID	Average	Std. dev.	Minimum		Maximum	
	(cm)	(cm)	Antenna ID	(cm)	Antenna ID	(cm)
System1	175.48	-	TCVR1	175.48	TCVR1	175.48
System2	175.48	-	TCVR1	175.48	TCVR1	175.48
System3	175.48	-	TCVR1	175.48	TCVR1	175.48
System4	175.48	-	TCVR1	175.48	TCVR1	175.48
System5	175.48	-	TCVR1	175.48	TCVR1	175.48

System legend
iBwave / 5G NR / 3.5 GHz / TDD - 10 MHz - n78 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / 5G NR / 28 GHz / TDD - 50 MHz - n257 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / GSM / 900 MHz - GSM / P-GSM900 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / LTE / 1800 MHz - DCS / FDD - 10 MHz - Band 3 / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1
iBwave / HSPA PLUS / 2100 MHz - UMTS / HSPA2100 - block I 5 MHz / Sector number:: 1 / Nb. of channels: 1 / Nb. of sources: 1

Figure 11: Composite EMF compliance report when all 5 systems are active (Russian Federation)

Let's now repeat the exercise when we compare this distance with the compliance distance when only non-5G NR networks are active, and when all networks except m-MIMO 5G NR at 28 GHz are active. The results are shown in Table 5, in centimeters.

	Non 5G systems only	All systems active except m-MIMO	All systems active, including m-MIMO
Compliance distance, cm	63.1	74.6	175.5

Table 5: Compliance distance (cm) comparison with and without 5G NR networks (Russian Federation)

The increase in distance compliance when m-MIMO 5G NR is added is the highest among the three countries: 135%.

Let's now summarize results from Table 3-5:

Compliance distance, cm	**USA**	**Slovenia**	**Russia**
Non-5G systems only	7.8	22.6	63.1
All systems except m-MIMO	8.8	25.9	74.6
All systems including m-MIMO	18.15	56.5	175.5

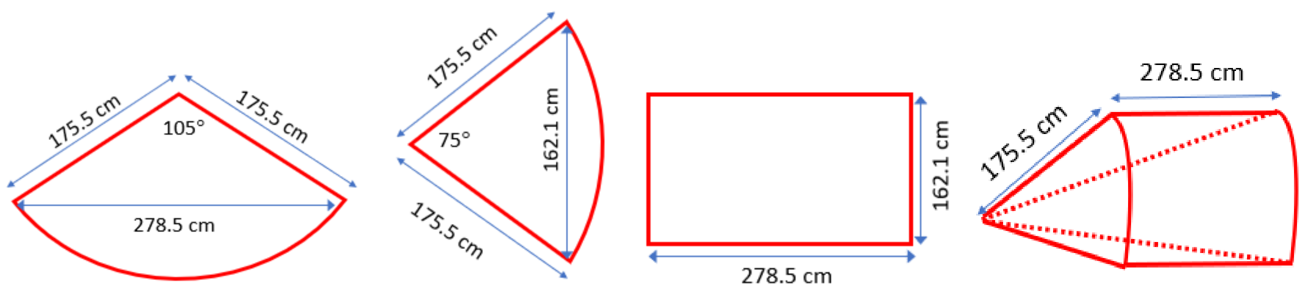
Table 6: Summary of EMF compliance distance, in centimeters, for multi-technology multi-band indoor systems in the three countries

As expected, the country with the strictest power density limit (Russian Federation) has the largest compliance distance. When comparing individual technologies in a multi-technology multi-band system, 5G NR with deployed m-MIMO technology has the greatest influence on compliance distance.

3.5 EMF RADIATION COMPLIANCE IN THE CONTEXT OF m-MIMO 5G NR

Let's now take a look at what EMF compliance distance really means in the context of m-MIMO 5G NR network. In Section 3.1 we mentioned that for 2G, 3G and 4G networks compliance distance is a point in broadside direction, where antenna gain has its maximum value, Ag. For an m-MIMO system, this is a two-dimensional collection of points, each point corresponding to an individual m-MIMO beam.

As per Figure 5, the m-MIMO system we used in the compliance distance calculation examples has 35 individual beams: 7 in horizontal plane and 5 in vertical plane. Each beam is 15º wide, and thus these 35 beams cover a 105º angle in horizontal plane and a 75º angle in vertical plane. Thus, a compliance distance for an m-MIMO system is in fact a 3-dimensional exclusion zone. This is depicted in Figure 12 below.



(a) (b) (c) (d)

Figure 12: (a) horizontal cut (b) vertical cut (c) broadside view (d) 3D view of m-MIMO EMF compliance exclusion zone

m-MIMO systems have highly directional antenna pattern. Such pattern significantly increases compliance distance in direction of m-MIMO beams. However, outside of those beams, there is little EMF radiation. Calculating only compliance distance is enough for omni-directional antennas as those antennas radiate almost the same EM energy in all directions. However, knowing only EMF compliance distance for m-MIMO and assuming it applies in all directions around the antenna panel would vastly overestimate harmful EMF radiation. m-MIMO EMF radiation exclusion zone is a three-doimensional boundary that encompases all m-MIMO beams. Inside the zone m-MIMO beams transmit almost all EM energy. Outside of that zone the beams transmit very little, and thus EMF radiation level is acceptable.

Computing EMF radiation exclusion zone dimensions gives us a better idea where excessive EMF radiation is. In this particular example, instead of assuming that the safe EMF radiation distance is 175 cm in all directions around the panel, we localized the harmful radiation area to be within a 278.5 x 162.1 cm rectangle, 175.5 cm away from the panel in the broadside direction.

4 SUMMARY

The topic of harmful EMF radiation has been debated a lot recently in the context of 5G network deployment. The main international body that addresses this topic is International Commission on Non-Ionizing Radiation Protection (ICNIRP). Based on scientific medial research, they specify EMF radiation limits, which are adopted “as is” by some countries around the world. However, many countries prefer to impose stricter limits that are 10 times or even 100 times less than the ICNIRP recommendations. We gave an overview of EMF exposure limits for selected industrial nations around the world and compared them against each other. We also explained the theory behind EMF radiation compliance distance calculation. We examined how that distance varies for multi-technology multi-band in-building networks in a few countries that have vastly different EMF radiation exposure limits. We also discussed how adding 5G NR networks to existing in-building systems affect the compliance distance. We identified massive MIMO (m-MIMO) as technology that impacts the compliance distance the most. We also introduced the concept of EMF radiation exclusion zone, how it relates to compliance distance, and where it is appropriate to use exclusion zone instead of compliance distance.

5 REFERENCES

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