5G Technology: Which Risks From the Health Perspective?

Luca Chiaraviglio, Marco Fiore and Edouard Rossi

Abstract The deployment of a new generation of mobile communication networks requires the installation of a dedicated radio access infrastructure. In the case of 5G, this unavoidable practice is creating a controversy about the potential issues for the public health that new radio base stations may entail. In this chapter, we discuss five major health risk allegations against 5G, namely: (*i*) the links between insurgence of tumors and exposure to ElectroMagnetic Fields (EMFs) generated by 5G; (*ii*) the increase of EMF levels due to an uncontrolled proliferation of 5G sites; (*iii*) the health risks associated to emissions in the new mm-Wave spectrum adopted by 5G; (*iv*) the uncertainty about the actual 5G EMF emission levels caused by the absence of dedicated measurements; (*v*) the impossibility to remove the previous uncertainty determined by the lack of measurement tools suitable for 5G technologies. We examine these arguments from an engineering perspective, by tacking into account the outcome of state-of-the-art scientific studies, the current relevant regulations and the technical features of 5G technologies. Our review indicates that there is no incontrovertible scientific evidence supporting any of the five claims. While we second the need for further investigations, we also remark a factual fabrication of *fake news* on the risks of 5G for the public health, which may severely distort the perception of this technology by the population at large.

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1 Introduction

An excerpt from a January 1900 article of a reporter based in Portsmouth, New Hampshire [1] reads: *"Electric, electric, electric!* [...] *The untapped electrical fluid leaking from these outlets and wires, we are told, may cause serious bodily damage and –with prolonged exposure– possibly death. We are certainly gaining momentum in this Modern Day, but can anyone tell us where we are headed?"*. Almost 120 years later, electricity is a globally widespread technology that is instrumental to the daily activities of billions and is considered completely secure –as long as it is handled abiding by minimum safety standards.

Today, a similar controversy arises concerning the fifth generation (5G) of wireless communication systems. As 5G heads into commercialization after a decade of research and development, arguments are made about the potential risks of the technology for the public health. The fear of 5G, propagating via social media and fuelled by an apparently diffused belief that the economic interests of industries and governments may be the sole drivers for the deployment of the new technology, has grown to the point of pushing politicians to publicly advocate for experimental trials to be withhold in major cities in Europe [2].

Are these worries justified, or are we facing a similar unnecessary anxiety as that recorded for electricity early into the twentieth century? To help shedding light on this matter, we present and discuss five main allegations against the installation of 5G radio base stations, stemming from the potential negative effects that the new infrastructure may have on public health. Our analysis is carried out from a purely technical perspective, by leveraging multiple sources of information that include the applicable Italian regulations on EMF emissions, the technological characteristics of 5G radio base stations, and the results of scientific studies on the effect of EMF exposure on living beings. As such, we offer a different viewpoint from that adopted by works in the literature that focus on clinical or medical considerations about EMF exposure (see, *e.g.*, [3]). Differently from the medical/clinical field, our goal is in fact to better contextualize potential health risks with respect to the actual engineering of 5G networks.

We remark that our examination concerns the possible health dangers associated with the deployment of new 5G radio base stations. In other words, we aim at better understanding if there are evidences that the EMF that will be generated by the 5G radio access infrastructure may jeopardize the health of citizens. This choice is motivated by the consideration that distress in the public opinion is generally connected to the installation of new base stations. However, the reader should be aware that this chapter only explores one facet of the problem: other potential risks, which are less criticized, may exist, in particular with regards to the *personal consumption* of new communication technologies. Indeed, a more frequent utilization of smartphones determined by the growing compulsion for mobile services causes an inherent higher exposure of individuals to the EMFs generated by the end terminals themselves –which, in fact, are often the main source of EMFs in the proximity of users already today [3, 4, 5, 6].

In the remainder of the chapter, we first review each of the five allegations on health dangers associated with the installation of 5G radio base stations in Sections 2 to 6. Based on these reviews, we draw conclusions and discuss opportunities for future research in Section 7.

2 Allegation I: Exposure to EMF generated by 5G radio base stations increases the risk of developing tumors

The first and most prominent dispute is that exposure to the EMFs of 5G radio base stations (and in fact to radio-frequency transmissions in general) induces a higher risk to develop specific classes of tumors. Claims in this sense are typically supported by citations to the following documents.

1. In two different studies released in 2018, the USA-based National Toxicology Program (NTP) experimentally proved that exposure to high levels of radiation from radio base stations, like those deployed for 2G and 3G mobile networks, is associated with the emergence of heart tumors in male rats [7, 8]. Also, the studies evidence a possibility that a higher incidence of brain and adrenal gland tumors is also correlated with radio base station emissions.
2. A study of the Ramazzini Institute, an Italian non-profit private organization, released shortly after those carried out by the NTP, corroborated the health risks associated with radio base station emissions [9]. Specifically, the research reports an increase in the incidence of brain and heart tumors in Sprague-Dawley rats exposed to EMF generated by a radio base station. In fact, a statistically significant increase in the incidence of heart Schwannomas was observed in treated male rats already at exposure levels much lower than those considered in the NTP studies, and compatible with those experienced by people on a daily basis.
3. The International Agency for Research on Cancer (IARC) classified in 2011 non-ionizing waves (including the waves generated on frequencies adopted by radio base stations) as *possibly carcinogenic* to humans. The IARC classification will be actually revised in the near future, also based also on the outcomes of the reports mentioned above. Non-ionizing waves are likely to be classified as *probably carcinogenic* to humans after such a revision.

To provide a sound analysis of the results above and subsequent claims, we first present the current regulations on EMF exposure limits. We then discuss the outcomes of the NTP and Ramazzini studies, as well as the IARC classification, also in the light of the EMF limits enforced by aforementioned applicable laws.

Table 1 EMF limits comparison of Italian [10, 11] and ICNIRP [12] regulations for general public areas, residential areas and proximity of a radio base station site to a sensitive place. The Italian limits are more stringent compared to the ICNIRP-based ones.

Areas	**Regulations**	
	ICNIRP	**Italian**
General Public	28 [V/m], $f \in (10, 400]$ [MHz] $1.375 \cdot f^{1/2}$ [V/m], $f \in (400, 2000]$ [MHz] 61 [V/m] $f \in (2-300]$ [GHz]	60 [V/m], $f \in (0.1, 3]$ [MHz] 20 [V/m], $f \in (3, 3000]$ [MHz] 40 [V/m], $f \in (3, 300)$ [GHz]
Residential	28 [V/m], $f \in (10, 400]$ [MHz] $1.375 \cdot f^{1/2}$ [V/m], $f \in (400, 2000]$ [MHz] 61 [V/m], $f \in (2-300]$ [GHz]	6 [V/m] for all frequencies
Site	None	Minimum distance constraints

2.1 Regulations on EMF emissions

The fact that high levels of EMFs are hazardous for human health has been very well known for decades, as proven by a vast scientific literature on the subject. Exactly for this reason, there exist strict regulations that limit the maximum amount of EMFs from radio-frequency and electrical sources that citizens shall be exposed to. The allowed EMF levels are determined based on the present knowledge we have about the health effects of radio emissions, with the goal of ensuring the public safety.

EMF limits are in fact not uniform globally, and the related legislation vary across countries. In our analysis, we will consider the EMF limits enforced in Italy. Where relevant, we will also refer to the limits defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), which are adopted in many countries worldwide, including most European countries. We summarize the two sets of limits in Table 1. Since the objective risks of EMFs, mainly involving heating of the radiated tissues, strongly depend on the frequency at which the EMF is generated, the limits vary with frequency. In addition, while the ICNIRP limits do not differentiate among the different portions of the territory, Italian regulations pursue a different strategy, and distinguish between general public areas where people do not stay for long amounts of time, and residential areas where people tend to live and work. Moreover, different municipalities in Italy, such as the city of Rome, adopt additional restrictions, typically by prohibiting the installation of radio base stations in proximity of sensitive places like public parks, hospitals, or schools.

The frequencies concerned with 5G and other mobile communication technologies are all above 400 MHz. Therefore, by looking at Table 1, it is evident that Italian laws impose limits that are already stricter than those recommended by ICNIRP for general public areas (at 20 [V/m]), and substantially lower in residential areas (at 6 [V/m]). In general, the ICNIRP limits are such that a lower EMF exposure does not produce any known hazardous effect on health. The Italian limits are much more stringent on the basis of a precautionary principle, so as to consider the potential impact of still unknown health effects. In the following, we will only consider the nationwide limits applied in Italy, and disregard further constraints that

Table 2 Tests performed in the NTP studies [7, 8], reporting the test name, the adopted frequency, the values of EMFs measured during each test, the average EMF over 24 hours, the positioning of the EMF and the 24-hour EMF with respect to the Italian limits.

Test	Frequency	Test EMF	24h EMF	EMF ≥ 20 [V/m] limit?	24h EMF ≥ 6 [V/m] limit?
GSM High	900 [MHz]	291 [V/m]	111 [V/m]	Yes, 15 times higher	Yes, 19 times higher
GSM Med	900 [MHz]	206 [V/m]	78 [V/m]	Yes, 10 times higher	Yes, 13 times higher
GSM Low	900 [MHz]	147 [V/m]	56 [V/m]	Yes, 7 times higher	Yes, 9 times higher
GSM High	1900 [MHz]	257 [V/m]	98 [V/m]	Yes, 13 times higher	Yes, 16 times higher
GSM Med	1900 [MHz]	178 [V/m]	68 [V/m]	Yes, 9 times higher	Yes, 11 times higher
GSM Low	1900 [MHz]	126 [V/m]	48 [V/m]	Yes, 6 times higher	Yes, 8 times higher

may be imposed by local administrations. These are highly heterogeneous, hence too involved to discuss –although their application may further reduce the EMF exposure of inhabitants due to radio base station emissions.

It is also important to mention that the EMFs values to be compared against a limit are computed in a different way by two models. In both cases, these values are computed as an average of the EMFs measured over a time interval of a fixed duration. However, the ICNIRP limits consider an averaging interval of 6 [minutes] (currently under revision, with proposals to increase the interval up to 30 minutes), whereas the Italian limits are enforced on an average EMF computed over 24 hours for residential areas and over 6 minutes for general public areas, respectively. Therefore, when analyzing the EMF levels reported by different studies in the literature, we will apply suitable scaling factors to align them with the EMF measurement conditions prescribed by law. For instance, an EMF measured at a specific location of 10 [V/m] over 18 hours plus 0 [V/m] over the 6 subsequent hours correspond to an average EMF of 7.5 [V/m] over 24 hours. This last value is the one that must be used to verify adherence to the limits set by the relevant Italian laws.

2.2 A review of the NTP studies

As mentioned before two studies carried out by NTP showed a higher emergence of heart tumors in male rats exposed to EMF similar to those generated by 2G and 3G radio base stations [7, 8]. Table 2 summarizes the settings of the experiments reported in the NTP studies. The table details: the test name, the operating frequency, the EMF exposure of patients considered in the experiments (computed as the average EMF over the different chambers used in the test), the 24-hour average EMF,[1] the comparison of the EMFs against the Italian limit of 20 [V/m] for general public areas, and the comparison of the 24-hour EMF against the Italian limit of 6 [V/m] for residential areas. Based on the table, several considerations are in order.

[1] We assume that the average EMFs reported in [7, 8] are computed from the EMF values recorded during the exposure window (which is set to 9 hours and 10 minutes per day). Therefore, the 24-hour average EMF is scaled by $\frac{9\text{[hour]}10\text{[minutes]}}{24\text{[hours]}}$ times the value of EMF reported in the NTP studies. This is a conservative assumption to compare the 24-hour EMF against the 6 [V/m] Italian limit.

First, the technology taken into account in both studies is the GSM one[2], which was part of second generation (2G) mobile networks. Newer generations of radio base stations (implementing 3G, 4G and the forthcoming 5G networks) are demonstrably more effective than 2G base stations in reducing the radiated power, and consequently their induced EMF levels. Therefore, the outcome of both studies is not representative of 3G, 4G or 5G technologies, but just of higher-radiating 2G base stations whose usage is today generally limited in developed countries.

Second, the EMF exposure levels in both studies are inflated at values that are orders of magnitude higher than the EMF levels measured in proximity to users from cellular networks under operation, as shown, *e.g.*, by the recent survey of Sagar *et al.* [6]. Actually, both NTP studies place the 2G radio base station very close to the radiated animals, at a few meters of distance. Instead, in operational networks, the closest base stations are typically tens or hundreds of meters away from the user, as they are placed on top of poles and above rooftops of soaring buildings. Moreover, the zone in proximity to the base station is generally also made not accessible to the public. This makes the exposure conditions assumed by the NTP studies unrealistic from an engineering viewpoint.

Third, the aforementioned settings adopted by NTP result in EMF levels that are largely beyond the Italian EMF limits, *i.e.*, between 6 and 15 times higher than the general public area limit of 20 [V/m], and between 8 and 19 times higher than the residential area limit of 6 [V/m]. In fact, such EMF levels are well above the international limits defined by ICNIRP, *i.e.*, 41.25 [V/m] for the 900 [MHz] band and 59.93 [V/m] for the 1900 [MHz] band, respectively. As a result, the conditions reproduced in these experiments are not encountered in an operational network in Italy or Europe. In fact, the levels of EMFs considered in the studies are so high that they would even trigger tissue heating effects.

Fourth, as also reported by a note of ICNIRP [13], the NTP measured a survival rate of male rats not exposed to any source of EMF significantly lower than the ones exposed to EMFs, for all the tests. This issue may have also introduced a bias in the presented results, as the different lifespan of rats may have impacted the tumor emergence probability.

Based on the previous observations, we conclude that the NTP studies [7, 8] do not report any evidence of carcinogenicity if the EMFs generated by the radio base stations are below the limits imposed by the Italian law or recommended by ICNIRP. We remark that such limits are enforced for all cellular network technologies under operation, including the forthcoming 5G ones.

2.3 A review of the Ramazzini Institute study

The study of the Ramazzini Institute reports a higher incidence of brain and heart tumors in rats exposed to EMF generated by a radio base station [9]. Table 3 illus-

[2] The NTP studies cover also CDMA-based 2G radio base stations, for which similar conclusions hold, and not reported here for the sake of brevity.

Table 3 Tests performed in the study of the Ramazzini Institute [9], reporting the test name, the adopted frequency, the values of EMFs measured during each test, the average EMF over 24 hours, the positioning of the EMF and the 24-hour EMF with respect to the Italian limits.

Test	Frequency	Test EMF	24h EMF	EMF ≥ 20 [V/m] limit?	24h EMF ≥ 6 [V/m] limit?
GSM 5	1800 [MHz]	5 [V/m]	4 [V/m]	No	No
GSM 25	1800 [MHz]	25 [V/m]	20 [V/m]	Yes, 1.3 higher	Yes, 3 times higher
GSM 50	1800 [MHz]	50 [V/m]	40 [V/m]	Yes, 3 times higher	Yes, 8 times higher

trates the settings of the tests performed by the Ramazzini Institute, by detailing: the test name, the considered frequency, the rat EMF exposure measured during the experiment, the 24-hour average EMF,[3] and the positioning of such EMF with respect to the Italian limit of 20 [V/m] for general public areas and of 6 [V/m] for residential areas.

In fact, the study found a statistically significant increase of one disease (*i.e.*, the Intramural Schwannoma) only for male rats exposed to an EMF of 50 [V/m], labelled as test GSM 50 in the table. In addition, no statistically significant increase of diseases has been found for female rats, as well as when the male and female subsets are considered together, for the same test. By analyzing the values reported in Tab 3, we can note that the test GSM 50 considers exposure levels that are largely beyond the maximum EMF limits alowed in Italy. More precisely, the EMFs in this test are 3 times higher than the general public limit and 8 times higher than the residential area limit. All the other tests, considering lower EMFs (namely test GSM 5 and test GSM 25), did not find any evidence of health risks associated to the EMF emissions by the radio base station.

In all cases, similarly to the NTP studies, these tests were conducted in conditions not applicable to users served by a real-world modern cellular networks. These include (*i*) rats being placed at a very short distance of a few meters from the radio base station, (*ii*) the adoption of an outdated and power-inefficient technology, i.e., the 2G one. We believe that such settings severely limit the generalization of the results to base stations deployed in cities in developed countries, which are generally located far from the users and radiate a lower EMF compared to 2G.

In the light of these considerations, we conclude that, also in the case of the Ramazzini Institute study [9], there is no proof of carcinogenicity of the EMFs generated by radio base stations that operated within the Italian limits.

2.4 Comment on the IARC classification

As reported by a dedicated note of ICNIRP [13] and outlined above, the studies from NTP and the Ramazzini Institute have limitations that do not allow substantiating the carcinogenicity of radio-frequency EMFs generated by radio base stations. Con-

[3] The 24-hour average EMF is computed by scaling the EMF imposed during the experiment (i.e., 5 [V/m], 25 [V/m], 50 [V/m]) by the factor $\frac{19 \text{ [hours]}}{24 \text{ [hours]}}$, since the experiment duration of [9] is set to 19 [hours] per day.

sequently, it is not expected that the IARC will change the classification of EMFs from possibly carcinogenic (level 2B) to probably carcinogenic (level 2A).

In any case, we remind that, even for carcinogens at the maximum level (level 1), the dose plays a crucial role in determining the carcinogenicity of the substance/mixture/exposure. For example, a low dose of a carcinogen may have no impact on health. So far, there are no evidences that exposure to EMFs generated by radio base stations under realistic conditions (*e.g.*, distance from the radio base station in the order of dozen meters and more) and received EMFs below the Italian EMF limits are hazardous for the public health.

3 Allegation II: 5G will bring an uncontrolled proliferation of radio base stations and EMF levels

A second dispute related to health risks of 5G is that the deployment of this technology over the territory will result in an uncontrolled proliferation of 5G radio base stations and consequently of EMF levels. This allegation is somehow linked to speculations that the Italian EMF limits will be increased from the current 6 [V/m] limit to 61 [V/m] defined (for the 2-300 GHz band) by ICNIRP, in order to ease the installation of such a large number of new radio base stations.

We first consider the impact of deploying a large number of radio base stations in a portion of territory to formally demonstrate that, contrary to a common belief, this condition allows to steadily reduce the transmitted power of each base station, compared to the case in which few base stations are installed. In addition, we show with a simple numerical example that the average power radiated over the territory is not increased when the number of base stations is increased.

Let us assume a simple scenario, where the goal of the operator is to ensure that the power received from a radio base station in any served portion of the territory is above a minimum level, which is needed, *e.g.*, to guarantee the connectivity to users. Let us formally denote the received power and the minimum power level as P^R and $P^R_{\min}$, respectively. In our scenario, the operator has to ensure that $P^R \geq P^R_{\min}$ over the whole target geographical region. The received power P^R depends on the power emitted by each radio base station, denoted as P^E. In order to compute P^R from P^E, we need to consider the attenuation affecting the electromagnetic wave that traverses the air on the path between the radio base station and the portion of territory served by the base station. More formally, we need a propagation model that defines how P^E is reduced with distance, and use that to retrieve P^R. In our illustrative example, and for the sake of clarity, we will consider a simplistic model where the emitted power is scaled by the distance d from the serving base station, elevated to a path loss exponent γ.[4] The relationship between P^R and P^E is then expressed as:

[4] More complex models integrate also other features, such as the antenna gain, the fading effect and the working frequency. These terms are intentionally omitted here, as they are not needed to prove our point.

$$P^R = \frac{P^E}{d^\gamma} \tag{1}$$

The value of γ typically depends on the attenuation conditions (*e.g.*, line of sight or non line of sight with respect to the serving radio base station).

Under this model, the condition that the minimum power level P^R_{min} be received in each portion of the territory is equivalent to the following equation:

$$\frac{P^E}{d^\gamma_{\text{max}}} = P^R_{\text{min}} \tag{2}$$

where d_{max} is the maximum distance between a portion of territory served by a given radio base station and the serving base station. Intuitively, d_{max} represents the maximum coverage distance of one radio base station over a portion of the territory.

Now, let us consider two cases with a different number of radio base stations. In the first one, our portion of territory is served by a set of uniformly distributed radio base stations, with maximum coverage distance and emitted power denoted as $d_{\text{max}}(1)$ and $P^E(1)$, respectively. In the second case, let us consider a set of uniformly distributed radio base stations, each of them with coverage distance $d_{\text{max}}(2)$ and emitted power $P^E(2)$. Let us assume that the number of radio base stations in (2) is higher than in (1). Under this assumption, the maximum coverage distance $d_{\text{max}}(2)$ is lower than $d_{\text{max}}(1)$, due to the fact that, with a larger number of radio base stations, each of them has to ensure a lower coverage radius to serve the portion of territory under consideration. Let us denote with k the ratio between $d_{\text{max}}(1)$ and $d_{\text{max}}(2)$:

$$k = \frac{d_{\text{max}}(1)}{d_{\text{max}}(2)} \tag{3}$$

By applying Equation (2), we get:

$$\frac{P^E(2)}{d^\gamma_{\text{max}}(2)} = P^R_{\text{min}} = \frac{P^E(1)}{d^\gamma_{\text{max}}(1)} \tag{4}$$

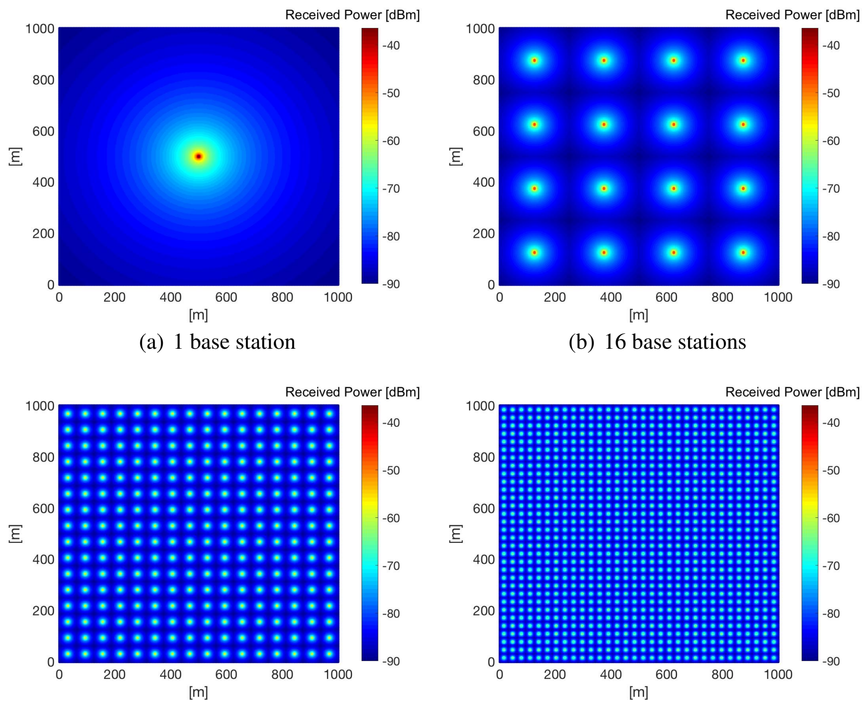
By considering the equivalence of the first and the third term and by adopting Equation (3) to express $d_{\text{max}}(2) = \frac{d_{\text{max}}(1)}{k}$, we get:

$$\frac{k^\gamma P^E(2)}{d^\gamma_{\text{max}}(1)} = \frac{P^E(1)}{d^\gamma_{\text{max}}(1)} \tag{5}$$

which can be simplified to:

$$P^E(2) = \frac{P^E(1)}{k^\gamma} \tag{6}$$

The previous condition states that, when the number of base stations is increased (case (2) compared to case (1)), the emitted power from each base station is reduced by a factor k^γ. For example, if we consider $\gamma = 2$ (a common setting in the literature in case of free space propagation), a circle portion of territory, and circle coverage provided by the radio base stations, it holds that $k = 4$ when passing from one radio



(a) 1 base station

(b) 16 base stations

(c) 256 base stations

(d) 1024 base stations

Fig. 1 Power radiated over the territory for different number of base stations - in dBm scale. A minimum power level of -90 [dBm] is ensured. The close-in propagation model of [14] with a 5G base station frequency of 3700 [MHz] is adopted. The power radiated by each base station is reduced when the number of base stations is increased (Figures best viewed in colors).

base station in deployment (1) to 16 radio base stations in deployment (2). Therefore, the emitted power of each radio base station in deployment (2) is reduced by $k^\gamma = 16$ compared to deployment (1). This is beneficial for the received power P^R over the territory, which tends to be better distributed and in general not increased in case (2) compared to case (1).

To give more insight, Figure 1 reports the power radiated over the territory for different numbers of deployed base stations, by assuming a minimum received power of −90 [dBm], a 5G base station frequency of 3700 [MHz], the close-in propagation model of [14] (which is more complex and realistic for 5G compared to a model solely based on distance),[5] an isotropic radiation pattern of each base station (uniform in all the directions), and coverage of each BS corresponding to a Voronoi tessellation (which is computed from the positions of the base station sites).

[5] The shadowing component in the original model of [14] is not included in our work for the sake of simplicity.

In particular, when there is a single base station (Figure 1.(a)), the received power is clear higher than -90 [dBm] for a vast zone in the surroundings of the base station. Interestingly, as soon as the number of base stations is increased (Figures 1-(b),(c),(d)), it is possible to dramatically reduce the amount of power radiated by each base station, with a reduction of the zone where the received power is higher than −90 [dBm]. These outcomes are in accordance with the model presented in Equation (1)-(6). In addition, we compute the average power radiated over the territory, which is equal to: i) −77.03 [dBm] for 1 base station, ii) −77.76 [dBm] for 16 base stations, iii) −79.26 [dBm] for 256 base stations, and iv) −80.17 [dBm] for 1024 base stations. Therefore, we can note that the average power (and consequently the EMF) radiated over the territory is not increased when the number of base stations deployed over the territory is increased.

Summarizing, we report evidences that adding more base stations to serve a territory does not introduce an increase in the received power (and consequently of the EMFs) compared to the case in which few base stations are installed.

Clearly, in order to support the 5G service, new radio base stations will be installed over the territory. The 5G network will be run in parallel to the 2G, 3G and 4G radio base stations that are already deployed over the territory. In addition, each of these technologies is supported by a set of operators. These facts, coupled also by the very strict regulations that are enforced in Italy, allow us to hypothesize that 5G will *not* result into a large proliferation of new radio base stations. This is especially true in urban areas, where most of the sites hosting base stations are already saturated, *i.e.*, it is not possible to install new radio base stations without violating the 6 [V/m] limit. In any case, however, the installation of the new 5G radio base stations will be done in accordance to the EMF regulations. As a result, the EMF radiated over the territory will be strictly controlled.

Finally, concerning potential relaxations of the 6 [V/m] EMF limits in Italy, we recall that there is not a single EMF limit in Italy: as reported in Table 1, the EMF regulations include multiple EMF limits, depending on the portion of territory under consideration and the adopted frequency. Anyway, we could not find any supporting evidence that the regulator will increase the 6 [V/m] limit for residential areas.

4 Allegation III: 5G radio base stations will exploit mm-Waves, which are dangerous

The third dispute brought to demonstrate the danger of 5G is that this technology will exploit new frequencies, called mm-Waves, which have not been used before and whose impact on the health is not known. In this regard, we recall that 5G will *not* use exclusively the mm-Wave frequencies. Table 4 reports the outcome of the 5G frequency auction that was completed in Italy in 2018: the frequencies in the 5G auction include sub-GHz (at 700 [MHz]), sub-6 GHz (at 3700 [MHz]) and mm-Wave (at 26 [GHz]). In particular, the 700 [MHz] and the 3700 [MHz] frequencies are close to frequencies already used by 2G/3G/4G networks under operation. Actu-

Table 4 Outcome of the 5G frequency auction in Italy [15, 16]. The costs per MHz for the sub GHz and the sub 6 GHz frequencies are two orders of magnitude higher than the cost per MHz for mm-Wave frequencies.

Type	Frequency	Offered Band	Auction Base	Assigned Band	Final Cost	Cost per MHz
sub GHz	700 [MHz]	75 [MHz]	2110 [M€]	60 [MHz]	2039 [M€]	34 [M€]
sub 6 GHz	3700 [MHz]	200 [MHz]	396 [M€]	200 [MHz]	4346 [M€]	22 [M€]
mm-Wave	26 [GHz]	1000 [MHz]	162 [M€]	1000 [MHz]	164 [M€]	0.16 [M€]

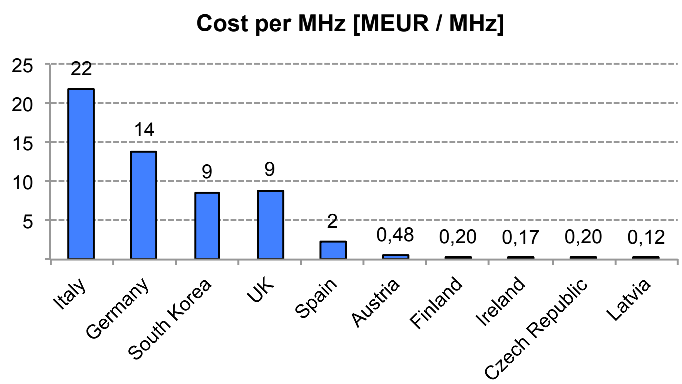


Fig. 2 Cost per MHz in the 3400-3800 [Mhz] spectrum in different countries in the world. The Italian cost per MHz is the highest one.

ally, the 700 [MHz] was used by another technology - the TV broadcasting - which will dismiss such frequency by 2021.

In fact, mm-Wave frequencies will only accommodate communication for niche services in 5G, and most traffic (hence EMF emissions) will occurr on bands that are largely used by previous generations of mobile networks. Let us analyze in more detail the outcome of the auction reported in Tab 4. The table reports for each frequency: (*i*) the total bandwidth offered in the auction, (*ii*) the total auction base, (*iii*) the total bandwidth that have been assigned to the operators, (*iv*) the total costs for the operators at the end of the auction, (*v*) the ratio between (*iv*) and (*iii*) (called "cost per MHz"). Several considerations are in order. First, the auction base was clearly higher for the 700 [MHz] frequency compared to the other ones, despite the fact that this frequency includes the lowest portion of bandwidth. Second, the most expensive frequency at the end of the auction resulted in the 3700 [MHz], whose cost passed from 396 [M€] when the auction was opened to 4346 [M€] when the auction was closed. Third, not all the bandwidth available at the 700 [MHz] was bought by the operators. However, the final cost incurred in this frequency was in the same order of magnitude compared to the 3700 [MHz] frequency. Fourth, the operators bought all the bandwidth offered at 26 [GHz] (i.e., the mm-Wave). However, the final cost (164 [M€]) was very close to the auction base (162 [M€]). Fifth, the final costs per MHz resulted in 34 [M€] and 22 [M€] for 700 [MHz] and

3700 [MHz], respectively, and only 0.16 [M€] for 26 [GHz]. By comparing the cost per MHz in the 3400-3800 [MHz] spectrum in different countries in the world (reported in Fig. 2), we can note that Italian operators have paid a cost per MHz much more higher compared to the one sustained in other countries (e.g., Germany, South Korea, UK, Spain).

It is thus clear that the largest investment of the operators for 5G was *not* on the mm-Waves, but on the 700 [MHz] and 3700 [MHz] frequencies. In particular, the 700 [MHz] frequency will allow to cover large portions of territory, while the 3700 [MHz] will bring a mixture of coverage and capacity. These two options appear to be the most promising ones for the operators compared to the 26 [GHz] frequency, which is instead tailored to the maximization of the capacity of users.

However, a natural question is then: Why are the operators not performing the same investment in the mm-Wave compared to the other frequencies? To answer this question, we need to remind that the government has imposed to the operators tight coverage constraints for the 700 [MHz] and 3700 [MHz] frequencies, while no coverage constraint is imposed on the 26 [GHz] frequency. In addition, mm-Waves are subject to very strong attenuation effects compared to lower frequencies. For example, mm-Waves are largely attenuated when passing through obstacles (*e.g.*, walls, buildings), resulting in poor signal levels (and consequently low capacity) in indoor environment. Therefore, we expect that the 5G technology will be realized mainly through the exploitation of the 700 [MHz] and 3700 [MHz] frequencies. In this scenario, the 26 [GHz] frequency will be exploited to cover selected portions of territory (not the whole one), where it will be possible to deploy, *e.g.*, small cells to limit the attenuation effects and bring high capacity to users.

Last but not least, we also remind that the potential impact of mm-Waves on health has been extensively studied in the past (see, *e.g.*, the survey by Zhadobov *et al.* [17]). Actually, the body scanners used in many airports in the world already use mm-Waves. Different studies were conducted to evaluate the impact of these waves on the health, as reported by the ICNIRP note [18]. Compared to lower frequencies, high levels of EMFs from the mm-Waves involve only heating of the skin and not of the inner tissues, due to the weak penetration properties of such frequencies [19]. However, the heating effects from mm-Waves are already excluded if the EMFs are below the maximum limits, which include all the frequencies up to 300 [GHz], and hence also the mm-Waves ones.

We can thus safely classify as *fake news* the fairly popular story of a storm of birds dying by flying in proximity of a mm-Wave 5G base station. By considering the power levels radiated by 5G base stations, which are in the range 100 [W]-200 [W] of maximum power [20], and current EMF limits, which are already enforced for 5G base stations, we can easily conclude that the power levels at which the 5G radio base stations operate are several orders of magnitude below the ones capable of producing any heat effect on a bird flying in proximity of the base station.

5 Allegation IV: There is a lack of experimental studies regarding the emissions of 5G radio base stations

The fourth dispute states that there is a threat on the population's health since no experimental studies showing the emissions of 5G radio base stations are currently available. In this scenario, the citizens are seen as lab-rats exposed to untested EMF field levels, especially in the towns currently hosting the 5G experimental trials.

In order to discuss such claims, we need to explain how power is radiated from a radio base station over the territory. The pre-5G technologies typically employ antennas which were sectorized to cover portions of territory falling inside a cone of radiated power, which starts from the base station site. The amplitude of the cone (for both its horizontal and the vertical components) depends on the technology as well as on the features of the antenna that is deployed. The 4G technology (in its latest revisions) integrates the possibility of placing more antennas working in coordination to serve the same portion of territory. Such technique, called Multiple-Input Multiple-Output (MIMO) (and deeply analyzed in subsequent Chapters of this book) allows an increase in the capacity provided to the users. Focusing now on the 5G, the antennas adopted by this technology will employ the MIMO communication, coupled with the possibility to concentrate beams of power over the territory, in order to increase the offered capacity in the zones where the users are actually located. Compared to the previous generations, therefore, the radiated power over the territory will be less uniform, as it will be varied over space and time.

However, it is expected that such smart antennas will be realized mainly for radio base stations running on the 26 [GHz] and the 3700 [MHz] frequencies (*i.e.*, those guaranteeing medium and large capacity). Given that such radio base stations are already being deployed on the territory (especially the ones on 3700 [MHz], see, *e.g.*, [21] for the network deployed in the city of Bologna), the Italian regional environmental protection agency (ARPA) is currently authorizing the installation of such radio base stations by simulating their EMFs under very conservative conditions (*e.g.*, maximum radiation pattern over all the directions) [20]. This choice provides safety to the population, since the actual EMF levels are in general lower than the ones assumed during the authorization phase. However, we also advocate the need to include in the Italian regulations exact procedures describing how to perform EMF value calculations to meet the limits for 5G radio base stations. Finally, as soon as the 5G network will become operative in Italy, we expect that measurements of EMFs generated by 5G base station equipment will be made publicly available by ARPA, as normally happens nowadays for other generations of mobile networks [22].

Table 5 Range and measured frequencies by two probes used to perform wideband measurements. These probes can be used to measure the EMFs generated by 5G radio base stations.

Type	Frequency Range	EMF Range	Sensitivity	Measurable 5G Frequencies
A [23]	100 [kHz] - 8 [GHz]	0.2 [V/m] - 130 [V/m]	0.2 [V/m]	700 [MHz], 3700 [MHz]
B [24]	20 [MHz] - 40 [GHz]	1 [V/m] - 1000 [V/m]	1 [V/m]	700 [MHz], 3700 [MHz], 26 [GHz]

6 Allegation V: It is impossible to measure the EMF levels of 5G radio base stations

The last dispute is that, since this technology will be run on new frequencies and will involve novel technology features (*e.g.*, MIMO and beamforming), it is not possible to realistically measure the EMF generated by a 5G radio base station.

We start by recalling some basics on the measurement of the EMF generated by a radio base station. First of all, EMF measurements performed with the many applications available for smartphones are to be considered unreliable, since end terminals have a very limited capability to assess physical layer properties in general and EMF levels in particular. Proper EMF measurements from radio base stations must be told apart into (*i*) measurements performed over a range of frequencies, called wideband measurements, and (*ii*) measurements performed on a specific frequency (excluding the other ones), which are typically referred to as narrowband (or selective) measurements. The choice of measurement approach (narrowband or wideband) severely impacts the type of equipment that has to be employed. For example, narrowband measurements typically require spectrum analyzers, while wideband measurements generally adopt less complex devices, *i.e.*, an EMF meter unit and an EMF probe. However, in both cases, the measurements need to be performed by qualified personnel, as these devices are not conceived to be used by the general public.

In the remaining of this section, we will assume to perform wideband measurements of 5G radio base stations (although narrowband measurements are being performed by ARPA, see, *e.g.*, [20]). In this scenario, Table 5 reports the type of probes currently sold by a producer of EMF meters and EMF probes. The table reports also for each type of probe the measurable frequency range, the minimum EMF sensitivity, the measurable EMF range, and the measurable 5G frequencies. Interestingly, the probes that are actually on sale are already compatible with the frequencies of 5G radio base stations. For example, the first probe is able to measure all the EMFs generated over the range 100 [kHz] - 8 [GHz] (thus including both the 700 [Mhz] and the 3700 [Mhz] 5G frequencies), while the second probe is able to extend the range up to 40 [GHz], which is well above the maximum 5G frequency of 26 [GHz] in use in Italy. Clearly, we expect that the minimum sensitivity will be improved in the near future (*e.g.*, the second probe has a minimum sensitivity of 1 [V/m]).

Focusing then on the impact of MIMO and beamforming on the measurements of EMFs, these features introduce a variation of the received EMF over space and over time components. The fact that the EMFs vary over time is not new, as current 4G networks already perform a time-variant scaling of the radiated power, in accordance to the traffic requested by users. The element of novelty is that in 5G the positioning of the radiating beams will be not known a-priori, as these beams may be used, e.g. to follow a user or a set users moving over the territory. Such features introduce an additional level of complexity in measuring the EMF radiated by a 5G base station, as the EMF measured in one point is impacted by the presence or the absence of beams focused on the measurement point during the measurement interval. For this reason, we expect that the regulators will introduce in the near future specific guidelines on how to measure the EMFs generated by the 5G radio base stations. For example, one way to face the unpredictability of EMF variations would be to employ a large set of EMF meters, by performing the measurements in parallel over the coverage area of the 5G base station under consideration. Clearly, such measurements should be repeated over time, in order to track the time-variability of the beams. Eventually, a second solution (currently requested by ARPA to different operators [20]) is to force the operator to generate beams that are fixed and are oriented towards the measurement locations.

7 Conclusions and Future Works

In this chapter, we discussed five main allegations regarding the potential health effects due to the EMFs generated by 5G radio base stations. By reviewing the relevant scientific documentations, we could not find evidences of carcinogenicity associated with an EMF exposure below the limits set by the applicable Italian laws. In addition, we clarified that an increase in the number of 5G radio base stations would only allow to steadily decrease the power (and consequently the EMFs) generated by each base station, while preserving the received signal strength (hence quality of communication) over the territory. In all cases, given the current regulations on EMF limits and the presence of pre-5G sites, we do not expect that 5G will bring to a huge proliferation of new radio base stations.

We have also shed light on the potential danger of mm-Waves, by: (*i*) providing evidence that 5G will be mainly based on frequencies that do not belong to the mm-Waves class; and, (*ii*) reporting the absence of scientific works that demonstrate health effects associated with an EMF exposure from mm-Waves below the limits. Also, the presumed lack of experimental studies of EMF emissions from 5G radio base stations does not seem factual, since it is possible to take into account the new features brought by 5G during the authorization and measurement steps.

While our work allows to conclude that most of the disputes against 5G radio base stations are not supported by scientific evidence, we would like to conclude our discussion by stressing the importance of continuing medical and clinical research. This is needed to evaluate any potential health impact of low EMFs generated by all devices, including the ones in close proximity to users, *e.g.*, 5G smartphones, tablets and laptops.

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