

Fig. 2. 5G communications engineering is the glue to analyze the different disciplines involved in the assessment of health risks from 5G exposure.

the assessment of (potential) health effects from 5G devices operating in the mm-Wave band [9], thus fuelling the argument that not enough research has been done to demonstrate the safety of 5G. Not surprisingly, part of the population is convinced that exposure to ElectroMagnetic Fields (EMFs) generated by 5G gNBs and 5G UE is dangerous for health [10].

Although the research community well knows that, at present time, there are no proven health effects from an EMF exposure kept below the maximum limits enforced by law (see e.g., [11]), the health risks associated with 5G are overly perceived by the general public.¹ This is (likely) due to multiple reasons, which include both rational and irrational aspects. In general, we observe: *i*) a widespread fragmentation of research across the different disciplines that are involved in the health risks assessment of 5G, *ii*) a diffuse feeling of a suspect against the institutions that are supposed to control the health risks of 5G, and *iii*) a continuous fabrication of fake news (misinformation), which generally convey the message of severe health risks triggered by 5G exposure in an immediate and catching way compared to the scientific community. For example, the misinformation or “infodemic” related to the connection between EMF exposure from 5G gNB and the infection of Coronavirus disease (COVID-19) disease [12] is currently very widespread in non-scientific communities.²

In this scenario, analyzing the scientific literature targeting the health risks of 5G is a fundamental task on one side and a challenging (and multi-faceted) problem. Indeed, the health risks assessment of 5G covers several disciplines, which include (to cite a few): medicine, biology, physics, economics, and laws. Although we recognize the relevance of each of the previous fields, the scientific research about health risks associated with 5G is frequently polarized towards a single aspect of the whole picture, with little attention to the other areas. For example, medical studies are often focused on assessing the health diseases triggered by 5G exposure (including legacy mobile generations), with little emphasis on the meaningfulness of the adopted test conditions. Also, the conditions of the experiments are often very conservative and

¹In line with the recommendations of international organizations (such as the World Health Organization (WHO) and the International Telecommunication Union (ITU)), we also advocate the need of continuing to investigate possible - yet still unknown at present - health effects due to 5G exposure, especially at higher frequencies.

²The “infodemic” expression has been used by the WHO to describe the excessive amount of misinformation regarding COVID-19 pandemic.

pretty far from the real settings of the radio equipment under operation in a deployed network. Since it is challenging to achieve a unique view of health risks across all the involved disciplines, the population tends to believe in the large number of fake theories/allegations claiming severe health risks triggered by 5G. Apparently, this issue also severely increases the sense of suspect against the institutions devoted to controlling health risks.

Given this background, a key question naturally emerges: Is it possible to scientifically analyze the health risks associated with 5G through holistic work spanning across the different disciplines that are involved in the problem? Our ambitious goal is to provide an answer to this intriguing question. More concretely, we adopt a 5G communications engineering perspective as the glue that links the research works from the different fields into a unique big picture. Clearly, our goal is not to compete with the communications efforts done by health agencies on the theme, but rather to add another (important) voice in the wide topic of health risk assessment of 5G exposure.

As sketched in Fig. 2, communications engineering is a common denominator for all the disciplines involved in assessing the health risks associated with 5G. For example, communications engineering can provide insights about realistic patterns of power radiated by 5G equipment, allowing a realistic assessment of 5G exposure. On the other hand, communications engineering can drive the design of new 5G equipment and protocols tailored to the minimization of the EMFs and, consequently, of the health risks. In addition, the communications engineering can provide indications about the effectiveness of the laws that regulate the 5G exposure, e.g., to assess if some laws are too conservative or too relaxed compared to the real conditions at which 5G devices operate. In a nutshell, communications engineering is the *passe-partout* to analyze the health risks of 5G.

Our key contributions include:

- 1) the analysis of the medical research focused on long-term EMF exposure, by exploiting the 5G communications engineering knowledge;
- 2) the evaluation of the EMF metrics and the EMF regulations across all the countries in the world from the perspective of 5G communications engineering;
- 3) the overview of the methods to assess the exposure compliance w.r.t. the maximum limits when considering 5G equipment;
- 4) the analysis of the main 5G and beyond 5G technology features and their potential impact on the health risks;
- 5) the discussion of the mitigation techniques based on communications engineering that can be implemented to reduce the health risks of 5G.

A. Paper Positioning

Tab. I reports the positioning of our work w.r.t. the relevant papers [13]–[19] already published in the literature. Although we recognize the importance of such previous works, to the best of our knowledge, this is the first paper targeting the

TABLE I
POSITIONING OF THIS WORK AGAINST OTHER RELEVANT PAPERS ANALYZING THE HEALTH RISKS OF 5G TECHNOLOGY.

Work	Year	Health Effects from 5G Exposure	5G Exposure Metrics, Regulations and Compliance Assessment	Health Risks of 5G Features	5G Risks Mitigation
[13]	2018	Partially covered: authors mainly focused on works investigating the biological effects of pre-5G technologies (including generic mm-Waves).	Not covered	Not covered	Not covered
[14]	2018	Partially covered: <i>i</i>) brief overview of works investigating the health risks of pre-5G technologies, <i>ii</i>) review of the works investigating health effects from generic mm-Waves (not radiated by 5G antennas).	Partially covered: <i>i</i>) brief overview of the FCC regulations, <i>ii</i>) no discussion about other international guidelines, <i>iii</i>) compliance assessment procedure only briefly mentioned.	Partially covered: <i>i</i>) possible effect of 5G frequencies (only mm-Waves are mentioned, while sub-GHz and sub-6GHz frequencies are not reported at all), <i>ii</i>) impact of gNB densification only briefly analyzed.	Not covered.
[15]	2018	Not covered	Partially covered: <i>i</i>) only incident field EMF for gNB and no metric for UE, <i>ii</i>) impact of national regulations on gNB planning in a single country, <i>iii</i>) International Commission on Non-Ionizing Radiation Protection (ICNIRP) regulations briefly introduced, <i>iv</i>) compliance assessment procedure tailored to a single country.	Brief discussion, no comprehensive overview of the related works.	Partially covered: network based solutions for gNB.
[16]	2019	Partially covered: focus is on the research works investigating biological effects due to exposure from generic RF sources (not tailored to 5G emissions).	Partially covered: <i>i</i>) exposure metrics briefly mentioned, <i>ii</i>) incident EMF strength taken into account, <i>iii</i>) international guidelines only briefly mentioned.	Not covered	Not covered
[17]	2019	Not covered	Partially covered: <i>i</i>) Review of exposure metrics for gNB (and not for UE), <i>ii</i>) Brief overview of one international guideline and a set of national regulations (with a focus on Poland) for limiting the maximum EMF strength, <i>iii</i>) overview of a generic procedure for compliance assessment of exposure, <i>iv</i>) international compliance assessment procedures only briefly mentioned.	Partially covered: <i>i</i>) brief discussion on the impact of Multiple-Input Multiple-Output (MIMO), mm-Waves and densification without reviewing the literature.	Partially covered: authors briefly discussed the impact of strict regulations and the monitoring activities based on measurements.
[18]	2020	Partially covered: <i>i</i>) brief overview of the alleged health effects from RF exposure, <i>ii</i>) brief summary of medical studies investigating the impact of RF exposure on health.	Partially covered: <i>i</i>) detailed overview of exposure metrics, <i>ii</i>) brief overview of the international guidelines (with a focus on UE), <i>iii</i>) no overview of national regulations stricter than international guidelines, <i>iv</i>) assessment of compliance only introduced.	Covered in terms of basic 5G features (MIMO, densification, mm-Waves)	Partially covered in terms of network based and regulation based solutions (with a focus on EMF mitigation).
[19]	2019	Not covered	Partially covered: <i>i</i>) exposure metrics for gNB and UE, <i>ii</i>) brief overview of international exposure regulations, <i>iii</i>) no detailed analysis of country-specific exposure regulations, <i>iv</i>) limited analysis of compliance assessment procedures.	Not covered	Partially covered: <i>i</i>) network based (limited to resource allocation), <i>ii</i>) device based.
This work	2020	Full coverage of: <i>i</i>) basic principles of Radio Frequency (RF) exposure, <i>ii</i>) overview of the main allegations against 5G exposure (updated on 2020), <i>iii</i>) analysis of the animal-based and the population-based studies relevant to 5G.	In-depth review with main contributions: <i>i</i>) coverage of 5G exposure metrics for UE and gNB, <i>ii</i>) analysis of international regulations (updated on 2020), <i>iii</i>) analysis of local regulations and their impact on 5G deployment (data from more than 225 countries), <i>iv</i>) analysis of the state-of-the-art compliance assessment procedures (updated on 2020)	Comprehensive analysis of the impact from: <i>i</i>) MIMO and beamforming, <i>ii</i>) gNB densification, <i>iii</i>) mm-Waves, <i>iv</i>) connection of millions of devices, <i>v</i>) co-existence with legacy technologies (2G/3G/4G, radio and TV broadcasting, weather satellites)	Comprehensive overview of the solutions for gNB and UE: <i>i</i>) device based, <i>ii</i>) architectural based, <i>iii</i>) network based, <i>iv</i>) regulation based.
Work	Year	Health Effects from 5G Exposure	5G Exposure Metrics, Regulations and Compliance Assessment	Health Risks of 5G Features	5G Risks Mitigation

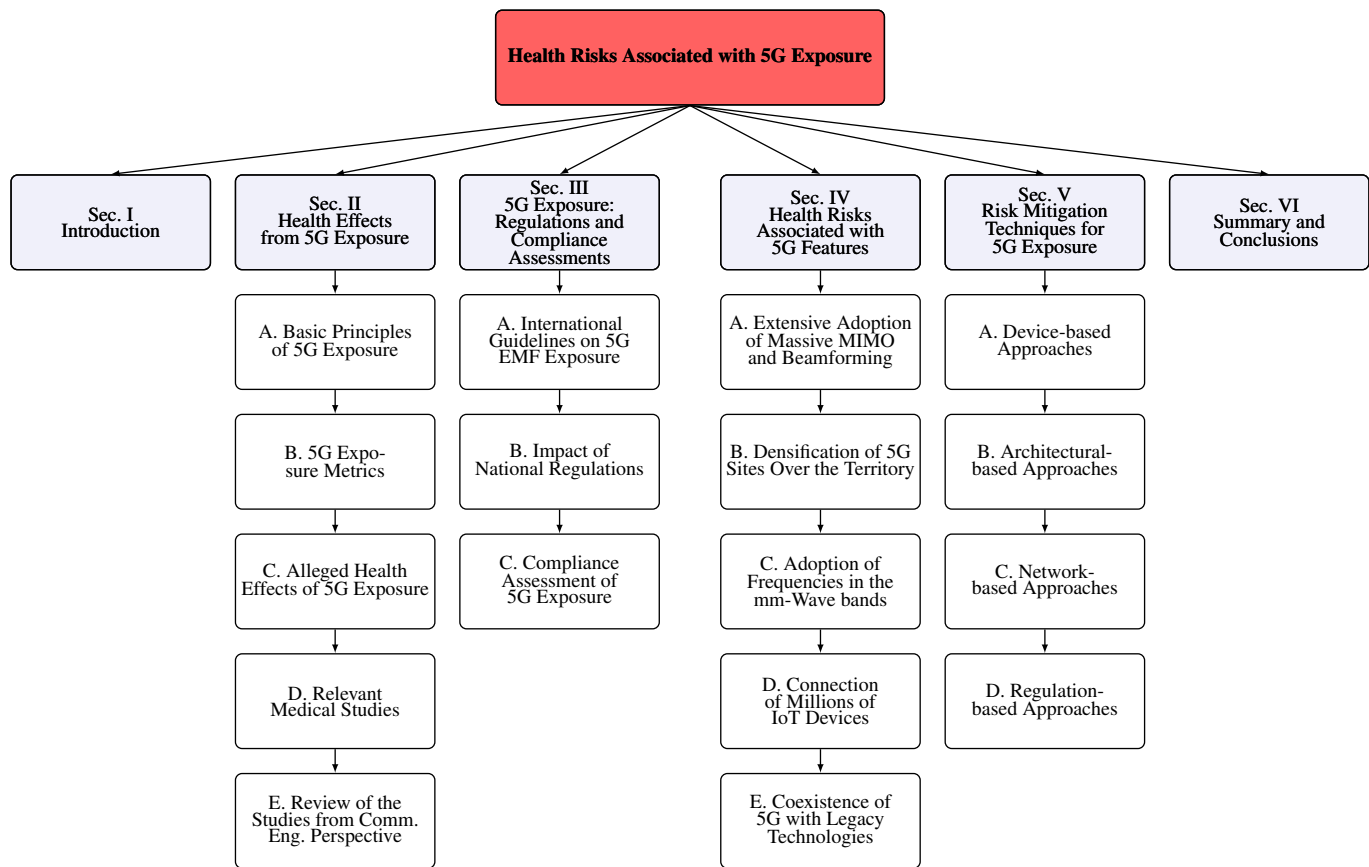


Fig. 3. Organization of our work.

analysis of health risks due to 5G by adopting a communications engineering perspective in a comprehensive and in-depth manner. Specific aspects of our work (and not covered by previous papers) include: *i*) a comprehensive approach that covers the health risks associated with exposure from both 5G gNBs and 5G UE; *ii*) a detailed analysis of the different 5G EMF metrics and the different 5G EMF regulations defined by international organizations (ICNIRP, Institute of Electrical and Electronics Engineers (IEEE)), federal commissions (Federal Communications Commission (FCC)) and even single nations (by extracting data from more than 225 countries); *iii*) the review of the latest guidelines from IEEE, International Electrotechnical Commission (IEC) and ITU to perform the compliance assessment of 5G exposure; *iv*) the risk analysis of the set of 5G features that are associated with health issues by the population; and *v*) the review of the main risk mitigation techniques at a device, architectural, network, and regulation levels.

B. Paper Organization

The rest of the paper is organized by following the scheme reported in Fig. 3. We initially analyze the health effects of 5G exposure in Sec. II. In particular, we briefly summarize the basic principles of 5G exposure. We then provide a concise overview of the exposure metrics that are relevant to 5G. In the following step, we overview the main health effects (particularly the negative ones) that are associated with 5G

exposure. We then provide an overview of the main medical studies that are relevant to 5G exposure. Finally, we review the main medical studies from the perspective of communications engineering, e.g., by considering the differences between the test conditions of such studies against the real settings at which 5G equipment operate.

Sec. III moves one step further in the risk assessment by reporting an overview of the international guidelines governing 5G exposure. In addition, the section focuses on the differences introduced by national regulations w.r.t. international guidelines, and on the impact that such regulations have on the perceived health risks of 5G. Moreover, we review the main procedures of the assessment of compliance of 5G exposure against the maximum limits defined by law.

Sec. IV is devoted to a review of the main allegations that are raised against specific 5G features. In particular, we tackle the impact of massive MIMO and beamforming on the perceived health risks. We then move our attention to the densification of cell sites over the territory, and its associated claims about a dramatic increase of exposure. In the following step, we consider the impact of frequencies in the mm-Wave bands on the health risks. Eventually, we tackle the issue of connecting millions of Internet of Things (IoT) devices per cell. In the following step, we discuss how 5G can coexists with other technologies, and how this feature will affect the health risks.

Sec. V focuses on the techniques that can be put into place

to mitigate the risks of 5G exposure. In particular, we survey the works targeting the reduction of exposure at the device, architectural, network and regulation levels.

Finally, Sec. VI concludes our work.

II. HEALTH EFFECTS FROM 5G EXPOSURE

We perform our analysis under the following avenues: *i*) basic principles of RF exposure, *ii*) summary of the alleged health effects from RF exposure, *iii*) overview of the relevant medical studies in the context of 5G communications, *iv*) critical review of these medical studies from the perspective of 5G communications engineering.

A. Basic Principles of RF Exposure

The exposure from EMF can be categorized according to the effects on the cells generated by the electromagnetic waves. In particular, we distinguish between ionizing radiations and non-ionizing radiations. The former category includes the waves that have enough energy to remove the electrons from the atoms in the living cells, causing the atom to become ionized. For example, X-rays with frequencies in the range 3×10^{16} [Hz] - 3×10^{19} [Hz] and gamma-rays with frequencies larger than 3×10^{19} [Hz] fall within the ionizing radiation. Depending on the dose level, the cells exposed to ionizing radiation may die or become cancerous, thus posing a risk for the health effects. On the other hand, EMFs belonging to the non-ionizing radiation group are composed of waves that do not have enough energy to ionize the cells, thus (likely) avoiding cancer and death for the exposed cells. However, the waves may have enough energy to vibrate the molecules, causing a possible health issue.

In this scenario, exposure from RF communications equipment falls within the non-ionizing radiation category. More specifically, the biological effects of RF radiation can be further classified into thermal effects and non-thermal effects. Focusing on the thermal effects, this group is characterized by an RF exposure that can produce a heating of the exposed tissues. An example of EMF source introducing thermal effects is the micro-wave oven (although this device is not intended to be used for RF communications). In this context, the mechanism that triggers the raising of the temperature in the exposed tissues is well understood and deeply analyzed in the literature, since the massive adoption of radio equipment for broadcast transmission [20]. To face this issue, regulatory authorities (e.g., the European Commission (EC) in Europe and the FCC in the USA), international commissions (e.g., ICNIRP) and international organizations (e.g., IEEE) define maximum RF exposure limits that allow preventing the heating effects on the exposed tissues.

Regarding the non-thermal effects, the majority of the literature and reports of international organizations state that there is not a clear causal correlation between EMF exposure levels generated by RF sources operating below maximum limits defined by law and emergence of biological effects, see, e.g., the Swedish radiation safety authority report [21], WHO and ITU statements [22]–[24], and recent ICNIRP guidelines [25]. However, since the mechanism by which the RF exposure

may cause non-thermal effects is still not entirely known (if there is any), it is essential to continue the research in this field.

Fig. 4 on the right shows the typical conditions of EMF exposure from RF devices, i.e., UE and base stations. In general, UE radiate close to users, by generating an EMF that is localized either on the head or chest. On the other hand, base stations radiate over the whole body and large portion of the territory compared to UE. However, the EMF generated by base stations tends to rapidly decrease in intensity as the distance from the RF source increases. Moreover, a shielding effect from base station EMF occurs inside buildings. Therefore, the exposure from base stations is, in general, lower compared to the one radiated from UE. Despite this fact, the population associates higher health risks to base station emissions w.r.t. UE radiation. In the following, we provide more details about the alleged health effects of RF exposure.

B. 5G Exposure Metrics

The main metrics that are used to characterize 5G (and pre-5G) exposure are: *i*) EMF strength, *ii*) power density, *iii*) specific absorption rate (SAR) value. In the following, we provide a concise definition of each metric. We refer the interested reader to [25] and references therein to obtain more details about exposure metrics for RF sources.

1) Electromagnetic Field Strength

Each RF source generates an EMF that is spread over the environment. The field is composed of an electric component and a magnetic one. Let us denote the electric field as \mathbf{E} , with a measurement unit in terms of Volt per meter [V/m]. Similarly, let us denote the magnetic field as \mathbf{H} , with a measurement unit in terms of Ampere per meter [A]. In general, both \mathbf{E} and \mathbf{H} are time-averaged values, i.e., they are estimated over a sufficiently long-time-interval (e.g., in the order of minutes [25]). Under far-field conditions, the EMF is characterized by solely analyzing \mathbf{E} . Otherwise, when the EMF is evaluated under near-field conditions, both \mathbf{H} and \mathbf{E} are needed to fully characterize the EMF strength.

Apart from time-averaged values, the EMF can be computed as an average from different points in the space. For example, the spatially averaged electric field strength E_{avg} over volume V is computed by applying a root mean square operation. More formally, we have:

$$E_{avg} = \sqrt{\frac{1}{V} \int_V |\mathbf{E}|^2 dv} \quad [\text{V/m}]. \quad (1)$$

2) Power Density

A second metric used to assess the level of exposure is the power density (PD), which can be either the absorbed power density S_{ab} or the incident power density S_{inc} . More formally, the absorbed power density S_{ab} is expressed as:

$$S_{ab} = \iint_A \frac{1}{A} \text{Re}[\mathbf{E} \times \mathbf{H}^*] ds, \quad [\text{W/m}^2], \quad (2)$$

where the body surface is at position 0 [cm], A [cm²] is the x-y integral area, \mathbf{E} is the electric field, \mathbf{H} is the magnetic field, ds is the integral variable vector whose direction is orthogonal

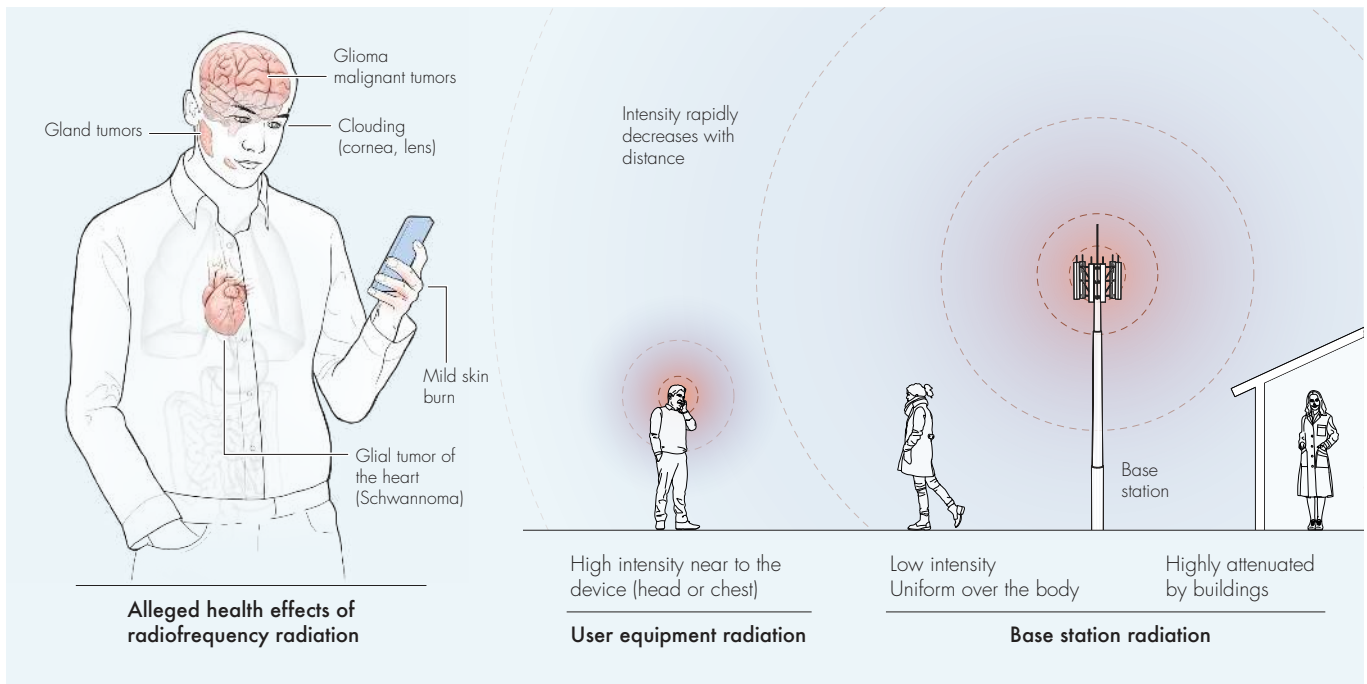


Fig. 4. Left part: main health effects that are alleged as a consequence of exposure from RF devices (including 5G equipment). Glioma and Schwannoma tumors have been observed only in animals exposed to high levels of EMF. Right part: the primary sources of EMF exposure when considering mobile network equipment. The EMF exposure from UE tends to be higher and more localized on the body than the one from radio base stations. Moreover, the EMF intensity rapidly decreases as the distance between the base station and the user is increased. Finally, buildings introduce a shielding effect that attenuates the exposure from outdoor base stations.

w.r.t. A , while $\text{Re}(\cdot)$ and $(\cdot)^*$ denote the real part and the complex conjugate, respectively.

The incident power density S_{inc} is defined as the modulus of the complex Poynting vector. More formally, S_{inc} is expressed as:

$$S_{\text{inc}} = |\mathbf{E} \times \mathbf{H}^*|, \quad [\text{W}/\text{m}^2]. \quad (3)$$

Under far-field conditions or transverse electromagnetic plane wave, Eq. (3) is simplified as:

$$S_{\text{inc}} = \frac{|\mathbf{E}|^2}{Z} = |\mathbf{H}|^2 \times Z, \quad [\text{W}/\text{m}^2] \quad (4)$$

where $Z = 377 \text{ } [\Omega]$ is the characteristic impedance of the free space. It is important to remark that Eq. (4) is also used when evaluating the equivalent power density metric (which is commonly denoted as S_{eq}).

Finally, the absorbed power density is related to the incident power density through the following equation:

$$S_{\text{ab}} = (1 - |\Gamma|^2) \times S_{\text{inc}}, \quad [\text{W}/\text{m}^2], \quad (5)$$

where Γ is a reflection coefficient, which depends on multiple physical features (e.g., the body tissue and/or the clothing above the body). We refer the interested reader to [25] for a more detailed overview of such properties.

In general, the international guidelines define PD limits that are expressed in terms of maximum S_{inc} values, since the incident power density is easier to be measured compared to the absorbed power density S_{ab} .

3) Specific Absorption Rate

According to [25], SAR is the time derivative of the energy consumed by heating that is absorbed by a mass, included in a

volume of a given mass density. When considering biological tissues and/or organs, the SAR is expressed as:

$$\text{SAR} = \frac{\sigma}{\rho} |\mathbf{E}|^2, \quad [\text{W}/\text{kg}] \quad (6)$$

where σ [S/m] is the electrical conductivity, ρ [kg/m³] is the density of the tissue/organ, and \mathbf{E} [V/m] is the internal electric field.

Under not significant heat loss processes [25], it is possible to express the SAR by considering the temperature rise. More formally, we have:

$$\text{SAR} = c \frac{\Delta T}{\Delta t}, \quad (7)$$

where c [J/(kg · Celsius)] is the tissue specific heat, ΔT [Celsius] is the temperature rise, and Δt [s] is the exposure duration.

In general, limits considering SAR as exposure metric assume two distinct spatially-averaged values, namely whole body SAR and local SAR. The whole body SAR takes into account the body mass and the total energy absorbed by the body. On the other hand, the local SAR assumes a given (small) volume with a given (small) mass.

Measuring the SAR becomes challenging for assessing the compliance of the exposure w.r.t. the regulations for high frequencies (like the mm-Waves ones). When the frequency increases, the penetration depth of the wave decreases. Under such a condition, the temperature rise is more superficial, and the heat tends to be lost across the environment, as pointed out by [25]. On the other hand, it is feasible to measure the PD instead of the SAR for high frequencies. In general,

the majority of the regulatory standards assign a frequency threshold, denoted as f_{th} , after which the considered limits switch from SAR to PD. However, some regulations (like [25]) additionally include SAR limits also for frequencies larger than f_{th} , in order to apply a conservative assumption. In any case, all the regulations differentiate between whole body SAR and local SAR (e.g., head, chest).

C. Alleged Health Effects from RF Exposure

Fig. 4 on the left sketches the (main) health diseases that are associated with RF exposure. Although some diseases have been only observed in animals (and not in humans), the debate about possible health consequences due to RF exposure is a hot (and controversial) topic. For example, the impact of brain-related diseases, including brain tumors and/or sleeping disorders, is highly critical in modern society. To shed light on these aspects, we briefly summarize in the following the alleged health effects (including severe and not severe ones).

Cancer. The International Agency on Research on Cancer (IARC) listed non-ionizing RF radiation from cell phones in Group 2B as “Possibly carcinogenic to humans” in 2010 [26], [27], mainly based on the analysis of epidemiological studies. More recently, a subset of works (see e.g., [28]–[31]) have found a statistically significant increase of rare cancers (i.e., glioma malignant tumors in the brain, glial tumors of the heart, and parotid gland tumors) associated to RF exposure in rats.

Skin Effects. The RF exposure with high power density can lead to an increase in the temperature of the exposed body tissue [32]. However, a modest localized heat exposure can be compensated by the human body’s heat regulation system. High doses of absorbed RF exposure can cause a sensation of warmth in the skin, causing mild skin burns [33].

Ocular Effects. High levels of RF exposure with sufficiently high power density may cause several ocular effects [34], including cataracts, retina damages, and cornea issues.

Glucose metabolism. RF exposure may affect the Glucose metabolism process in human cells [35]. The effect can be noticed in the body organs exposed to high levels of EMFs, e.g., the brain.

Male Fertility. According to a subset of studies (see e.g., [36]–[38]) high levels RF exposure may be associated with negative effects on reproductive health in terms of sperm-fertilizing ability. However, the connection of such effects with RF exposure from communications equipment is to our best knowledge scientifically not proven.

Electromagnetic Hypersensitivity. Some individuals report that RF exposure causes several sensitivity symptoms to them, e.g., headache, fatigue, stress, burning sensations, and rashes. However, many independent studies (see, e.g., [39], [40]) have demonstrated that such symptoms are not correlated with the levels of RF exposure.

Spreading of the COVID-19 Disease. Recently, different fake theories claim that there is a connection between the RF from 5G equipment and the spreading of the COVID-19 disease [41]. In particular, the fake theories include:

- higher infection rates for regions of territory exposed to RF from 5G experimental trials (e.g., Wuhan region,

Lombardy region) compared to those not covered by 5G [42];

- a dangerous interaction at a cell level between the DeoxyriboNucleic Acid (DNA) and radiofrequency radiation (RFR) from 5G equipment, causing a fatal inflammation of lungs;
- a supposed interaction between the RiboNucleic Acid (RNA) of the COVID-19 virus and the mm-Waves of 5G devices .

Such fake theories are not based on any scientific evidence, although they are widespread among the population. According to the UK National Health Service (NHS) [43], the diffusion of fake theories trying to connect COVID-19 and 5G is outrageous and dangerous.

Oxygen Effects. Another allegation trying to link RF from 5G equipment and health diseases include *i)* a supposed oxygen absorption of 5G equipment out of the lungs, and *ii)* the increase of carbon dioxide due to the cutting of the trees to improve the signal coverage of 5G. Focusing on *i)*, this allegation is not based on any scientific base. Focusing on *ii)*, there is no plan to cut the trees to improve the signal coverage. As a result, the claimed increase in carbon dioxide emissions due to 5G is fake news.

Summary and Next Steps. Several health effects are associated with RF exposure, ranging from scientific-based ones to allegations based on fake theories. In the following subsection, we provide more details about the works that aim at shedding light on the connection between exposure from 5G equipment and the emergence of tumors, which is one of the most controversial aspects brought to the attention of the general public. We intentionally leave apart skin, ocular, and glucose metabolism effects, as these phenomena are observed only for EMF levels consistently higher than the ones radiated by 5G equipment. Therefore, using 5G equipment under realistic conditions guarantees that such effects do not occur in practice. Similarly, we also skip additional analysis about male fertility and electromagnetic hypersensitivity, as their connection with 5G communications is not scientifically proven [44], [45]. Other health effects, which are based on hoaxes and fake theories, are not further discussed.

D. Relevant Medical Studies in the Context of 5G Communications

We then focus our attention on the medical studies that are relevant to the exposure from 5G communications. Tab. II reports a high level overview of the studies considered in this work. In particular, we divide the related works according to the type of experiment, which can be either animal-based or population-based. Other types of studies, based e.g., on in-vitro and/or ex-vivo experiments (e.g., living tissues extracted from surgery) are intentionally not treated and left as future works.

1) Animal-based Studies

In this category, experiments are conducted on living animals (e.g., rats and mice), exposed to EMFs to mimic the exposure from gNBs and UE. The number of works falling in this category is vast, with hundreds of animal-based studies

TABLE II
MEDICAL STUDIES CONSIDERED IN THIS WORK

Category	Name	Summary	Review
Animal	NTP [28], [29] Ramazzini Institute [30]	Sec. II-D1	Sec. II-E1
Population	INTERPHONE [46], [47] Danish Cohort [48], [49] Million Women [50] Cefalo Case-Control [51]	Sec. II-D2	Sec. II-E2

that analyzed the potential health effects from RF exposure over the last four decades (see, e.g., [52]–[57]). However, the majority of works presents multiple issues, including an insufficient duration of the experiment to extract long-term indications, and/or a too-small number of animals to derive statistically significant conclusions which are not subject to large biases. To face these issues, different international organizations (such as WHO, National Toxicology Program (NTP), and other international bodies) have provided guidelines for the procedures that need to be followed by animal-based studies that investigate the emergence of severe diseases (e.g., cancer) [58]–[63]. For example, the promoted guidelines define a minimum number of animals to be used (e.g., at least 50 animals for each group), a minimum temporal duration of the experiment (e.g., 2 to 3 years), and a minimum number of EMF intensity levels (e.g., 3) [64].

In this scenario, the most recent (and relevant) studies that fulfill the above requirements are the NTP study [28], [29] and the study of the Ramazzini Institute [30]. In the following, we provide more details about each of the aforementioned research works.

NTP Study. NTP performed in [28], [29] one of the longest bioassay conducted so far to evaluate the impact of EMF exposure from RF equipment on rats and mice. The study addressed the 2G technology, but however it is frequently cited by the opponents of 5G. In the experiments performed by NTP, the animals were exposed to RF in special chambers for several hours per day until the natural death. The total duration of the experiment was set to 2 years, with an initial assessment done after the first 28 days, and a final one performed at the end of the experiment. RF equipment used to generate the EMF employed frequencies in the sub-GHz band for [28] and in the mid-band (i.e., above 1 [GHz] and below 6 [GHz] bands) for [29]. The radiated power of the RF equipment was adjusted to satisfy a given level of whole-body exposure in the chamber, with different exposure levels assigned to the chambers. In addition, the generated EMF levels were continuously monitored in each chamber, to verify the adherence of the exposure to the EMF level imposed during the experiment.

Focusing on the outcomes of the studies, we refer the reader to [28], [29] for a detailed analysis, while here we report a concise summary. In brief, the study conducted over the sub-GHz frequency [28] found clear evidence of carcinogenic activity in Sprague-Dawley male rats due to malignant Schwannoma of the heart. However, the same clear evidence of heart Schwannoma incidence was not found when considering the female rats. Besides, the incidence of other

tumors (e.g., malignant glioma of the brain) was also related to the RF exposure (when considering male rats again). In general, other severe diseases were also observed, without however, a clear connection to the RF exposure level. Focusing then on the study adopting the mid-band frequencies [29], no clear evidence of tumors was found by considering male or female rats. Eventually, the incidence of severe diseases may have been related to RF exposure (although the observed cases were not statistically significant). Finally, the outcomes of [28], [29] are also analyzed by [65], concluding that RF exposure may be capable of causing an increase in DNA damage.

Ramazzini Institute Study. This research work evaluated the impact of RF exposure on Sprague-Dawley rats [30]. More specifically, the rats were exposed from prenatal life until death to a EMF generated by a RF for several hours per day. Like the NTP studies, the rats were divided into multiple groups, each of them exposed to different EMF levels. The study found a statistically significant increase in the occurrence of a single disease (i.e., the heart Schwannomas), which was only observed in male rats exposed to the highest EMF level. No statistically significant increase w.r.t the exposure was found for the other diseases. Moreover, female rats did not report a statistically significant increase for any of the diseases. According to the authors, their findings corroborate the NTP studies [28], [29] and previous epidemiological research on cellular phones, e.g., [47], [66]–[68], thus making necessary a revision of the IARC classification of RF exposure [27].

2) Population-based Studies

The studies belonging to this category aim at investigating the relationship between people affected by severe diseases (e.g., brain tumors) and the level exposure from base stations and/or UE. We do not intentionally focus on population-based studies tailored to base stations exposure, due to the following reasons:

- 1) base stations represent a minor source of exposure compared to UE (as proven by previous works e.g., [69], [70]);
- 2) the exposure from base stations tend to be notably reduced as the distance between the base stations, and the user is increased (see, e.g., [71], [72]) and more in general when indoor conditions are experienced (see, e.g., [73]);
- 3) previous population-based studies (see, e.g., the note [74] of the American Cancer Society and the comprehensive work of [75]) did not found any causal relationship between the exposure from base stations and the increase in the risk of developing tumors.

Focusing then on population-based studies on UE exposure, it is well known that this RF source represents a major source of exposure in proximity to users (see e.g. [69], [70]). Therefore, we consider here population-based studies that aim at finding a causal correlation between emergence of tumors and UE exposure. The main works performed in the past, which are relevant also in the context of 5G, are: *i*) the INTERPHONE study [46], [47], *ii*) the Danish cohort study [48], [49], *iii*) the million Women study [50] and *iv*) the CEFALO case-control study [51]. In the following, we provide more details about each study.

INTERPHONE Study. The INTERPHONE Study [46], [47] was coordinated by IARC. The research, based on a very-large case-control approach, was performed across 13 countries in the world during the years 2000-2012. The project goal was to study the impact of UE usage in people that developed severe diseases (i.e., glioma, meningioma, and acoustic neuroma), which may be connected to the usage of UE. The number of people involved in the study was quite important, i.e., more than 5000 patients with glioma or meningioma and 1000 patients with acoustic neuroma. Also, a similar group of people, not affected by any of the tumors mentioned above, was also monitored. The adopted methodology involved several aspects (e.g., personal interviews and validation studies) in obtaining, as much as possible, reliable data about UE usage (e.g., duration and frequency of the calls), as well as other relevant information, e.g., UE model, network operator, localization of the calls, user mobility and adoption of headsets or hands-free devices.

The results of the study [46], [47] did not prove any connection between the usage of UE and the risk of developing glioma, meningioma, or acoustic neuroma. Eventually, an increased risk of glioma for the largest RF exposure level was observed. However, the presence of biases and errors in the data prevented a causal interpretation of such results. The reduction of these biases is targeted by [76], taking into account the INTERPHONE data collected in Canada during the years 2001-2004. By applying a probabilistic multiple-bias model to address the (possible) biases at the same time, the authors demonstrated that there was little evidence of an increase of tumors with the rise in UE usage. Eventually, the importance of investigating possible long-term effects due to the heavy usage of UE was advocated by the team involved in the INTERPHONE project.

Danish Cohort Study. The goal of the Danish cohort study [48], [49] was to investigate the risks of developing tumors for Danish people having a subscription with a cellular operator against the remaining of the Danish population not having any subscription. The study was updated continuously throughout the years, being the first version spanning the years 1982-1995 [48] and the latest one covering the 1990-2007 period [49]. The number of persons taken under consideration is huge, being the number of subscribers in [49] larger than 380000. The study did not show any link between the use of UE - even for more than 13 years - and the risk of developing tumors of the central nervous system. However, the principle adopted to distinguish between exposed people and not exposed people is solely based on their subscription with a mobile operator, without going into more in-depth details like the ones taken into account by the INTERPHONE project.

Million Women Study. A wide-scale approach is also pursued by the Million Women study [50]. The methodology involved a postal questionnaire, which was completed by 1.3 million middle-aged women in the UK for different times during the years 1999-2009. The survey included specific questions to assess UE exposure, which was posed two times during the considered period. The results of the study [50] showed that UE use was not associated with an increased incidence of glioma, meningioma, or tumors of the central

nervous system. However, it is important to remark that the study is based on self-compiled questionnaires, and therefore bias and errors may have been (unintentionally) introduced by the participants.

CEFALO Case-Control Study. The CEFALO case-control study [51] investigated the impact of UE exposure on young children and adolescents (with age 7-19) that developed brain tumors between 2004 and 2008 in Denmark, Sweden, Norway, and Switzerland countries. More than 350 patients were interviewed about UE usage (i.e., number of calls and call duration) and other relevant information, including, e.g., type of operator, number of subscriptions, starting and ending date of each subscription, adoption of hands-free devices, position of the UE during the usage, and (eventual) changes in the UE usage. Whenever possible, the retrieved information was also double-checked by analyzing the logs that were made available by mobile operators in a subset of countries. The outcomes were then compared against a group of other adolescents/children, not affected by brain tumors, thus acting as control subjects. Results confirmed that children/adolescents regularly using UE were not statistically significantly more likely to have been diagnosed with brain tumors compared to subjects not using the UE. Also, no increased risk in developing brain tumors was observed for children/adolescents receiving the highest exposure. Eventually, the subscription duration was statistically significant w.r.t. the risk of developing a brain tumor for a small subset of the participants, whose activity information was retrieved from the logs of the mobile operators. However, as recognized by the authors of the CEFALO study [51], this outcome might be affected by multiple factors, including *i*) a small cardinality of children/adolescent considered in the subset (only 35% of case-patients and only 34% of control subjects), *ii*) the fact that the UE might have been used by other people in the family and/or friends (i.e., not by the considered subject), *iii*) the possible presence of a reverse causality effect (i.e., children/adolescents affected by brain tumors use more frequently their UE compared to the ones not affected by the disease). Finally, the authors concluded that their work could not support a causal association between the use of UE and brain tumors.

E. Review of the Studies from the Perspective of 5G Communications

We now review both the animal-based studies and the population-based ones from the perspective of 5G communications.

1) Animal-based Studies

We compare the NTP and Ramazzini Institute studies [28]–[30] against 5G equipment under the following key metrics: *i*) operating frequencies, *ii*) test chambers vs. real deployment, *iii*) maximum radiated power, *iv*) power management, *v*) EMF exposure levels, *vi*) SAR levels, *vii*) transmission and modulation techniques.

Operating Frequencies. We recall that 5G will operate in three main frequency bands:

- 1) sub-GHz band (i.e., < 1 [GHz]);
- 2) mid-band (i.e., between 1 [GHz] and 6 [GHz]);

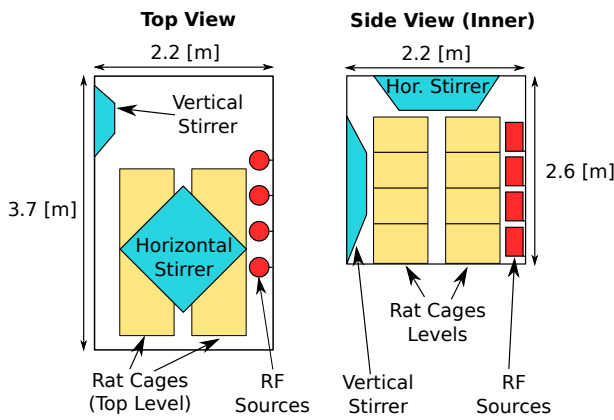


Fig. 5. Test conditions adopted in the NTP experiments. Multiple RF sources provide active exposure, while two stirrers (one horizontal and one vertical) are used as passive elements to generate an uniform exposure in the environment.

3) mm-wave (i.e., with frequencies in the order of dozens of GHz and more).

In this scenario, the NTP studies [28], [29] adopt frequencies belonging to the sub-GHz band and to the mid-band. More in-depth, the 900 [MHz] frequency used by [28] is very close to the one in use by 5G in the sub-GHz band. In Italy, for example, this frequency is set to 700 [MHz]. On the other hand, [29] exploits the 1900 [MHz] frequency, which is used for 5G services in some countries of the world (e.g., USA), while other ones (like Italy) adopt different frequencies. Focusing then on the Ramazzini Institute study [30], the adopted frequency is equal to 1800 [MHz], which is again comparable to the 5G frequencies in the mid-band.

Eventually, it is important to remark that none of the studies [28]–[30] investigate the impact of frequencies in the mm-Wave band, whose waves have very different properties (e.g., less penetration in inner tissues) compared to micro-waves. A natural question is then: Why do the studies in [28]–[30] not investigate mm-Wave? To answer this question, we need to remind that [28]–[30] assume to adopt 2G technologies (not 5G), for which the use of frequencies in the mm-Wave band was not possible. As a result, we can claim that the studies [28]–[30] are only partially representative of 5G frequencies.

Test Chambers vs. Real Deployment. We then compare the chambers used to perform the test against the real environment in which 5G equipment operates. We initially focus on the test chambers of the NTP studies [28], [29], which are also sketched in Fig. 5. We refer the reader to [77] for a detailed description, while here, we report the salient features. In brief, the NTP studies employed chambers whose dimensions are comparable to a small room. In each chamber, the rat cages are positioned in the center, with different levels of cages that are vertically stacked. Inside the chamber, many standard gain antennas are placed. The exact number of deployed antennas is not provided (neither in [28], [29] or in [77]). Besides, two elements, called stirrers, are placed on top and on the side of the chamber. Each stirrer is used as a target when setting the antenna tilting (with a subset of antennas directed towards the top stirrer, and the other ones towards the side stirrer).

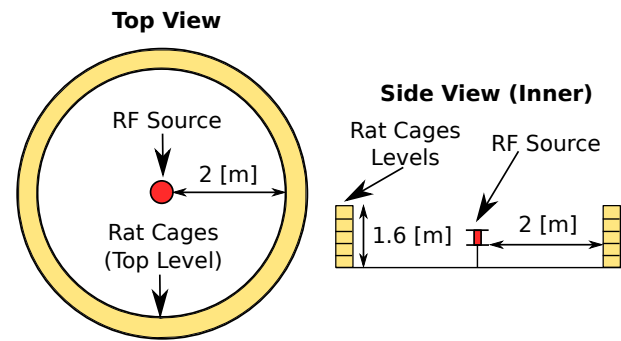


Fig. 6. Test conditions adopted in the Ramazzini experiments. The RF source is placed in close proximity to the exposed rats.

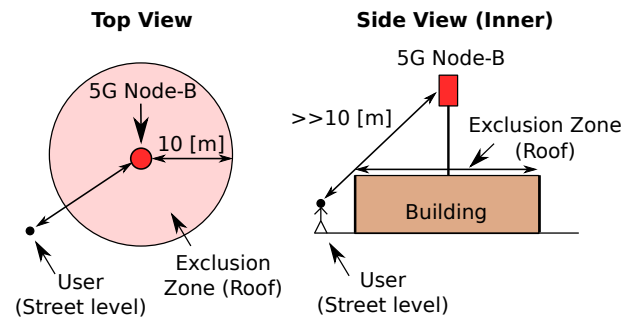


Fig. 7. Realistic conditions adopted in 5G gNBs deployments (macro sites). The exposed users in Line of Sight are always at dozens of meters from the radiating 5G gNB.

The stirrers are then used as passive elements to reflect the radiation and generate a uniform EMF across the chamber. In this scenario, both the antennas and the stirrers are placed in close proximity to the exposed rats.

Focusing on the test conditions adopted in the study of the Ramazzini Institute [30], the rat cages are disposed of in a torus structure around the RF source, as sketched in Fig. 6. Moreover, a minimum distance of 2 [m] is ensured between the RF source and the rat cages, to achieve far-field conditions. Eventually, the whole structure is placed in a chamber (not shown in the figure for the sake of simplicity) that is completely shielded, in order to create a uniform EMF in the room.

We then compare the test conditions of the studies [28]–[30] against a realistic 5G deployment of a macro gNB, sketched in Fig. 7. More in detail, we consider a 3.5 [GHz] omnidirectional gNB, mounted on a pole, and then placed on a roof of a building. A similar deployment, exploiting a three sectorial 5G gNB, is analyzed in [78]. In this scenario, the roof of the building delimits an exclusion zone from the center of the 5G gNB. Such a zone is intended to be accessible only by the technicians that need to perform maintenance operations on the 5G gNB. Clearly, this zone is forbidden to the general public, which is therefore physically prevented from entering. According to [78], a minimum distance to delimit the exclusion zone in a 5G deployment is in the order of 10 [m] from 5G gNBs. Consequently, we have imposed in Fig. 7 an exclusion zone of 10 [m], which delimits the roof of the building. As a result, users in Line-of-Sight (LOS) from

TABLE III
MAXIMUM OUTPUT POWER P_{MAX} FOR THE DIFFERENT DEVICES.

5G Device	Value	Reference
RF source - NTP	3800 [W] (65 [dBm])	[77]
RF source - Ramazzini Institute	100 [W] (50 [dBm])	[30]
5G macro gNB	200 [W] (53 [dBm])	[79]
5G UE	0.2 [W] (23 [dBm])	[80]

the 5G gNB tend to be pretty far from the source of radiation. By comparing the distance between the exposed users/rats and the radiating source, we can note that both the NTP study [28], [29] and the Ramazzini Institute one [30] assume a distance from the RF source much closer than the minimum distance from a radiated user in a realistic 5G deployment. This is a second and essential outcome that obviously differentiates the laboratory studies w.r.t. the real deployment of 5G gNBs.

In the following step, we compare the test chambers of [28]–[30] against the real conditions at which a 5G UE operates. First of all, it is important to remark that a 5G UE is also used outdoor, and not only in a chamber like in [28]–[30]. In addition, mobility is another important aspect that strongly impacts the exposure conditions of 5G terminals, which on the other hand, is not considered by the static deployment of [28]–[30]. Moreover, the distance between the UE and the exposed zone of the body is clearly lower than the one imposed in the NTP and Ramazzini Institute studies. Eventually, the exposure from a UE is not uniform across the environment like in laboratory studies, but it tends to be localized to the closest tissues/organs. Therefore, the test conditions adopted in [28]–[30] are clearly far from the actual operating conditions of a 5G UE.

Maximum Radiated Power. As a third aspect, we consider the maximum radiated power P_{MAX} of the RF sources employed in [28]–[30], and their comparison against real 5G communications equipment (i.e., a 5G macro gNB and a 5G UE). To this aim, Tab. III reports the comparison across the different types of devices adopted in the studies and the ones deployed in 5G networks. Two considerations hold in this case. First, the value of P_{MAX} adopted in the NTP study is one order of magnitude higher than the one used in a 5G macro gNB, and four orders of magnitude higher than the one of a 5G UE. Although the use of enormous radiated power values is also recognized by the authors of [28], [29], it is important to remark that such values are outside the operating range of realistic 5G gNBs. Second, the value of P_{MAX} used in the Ramazzini Institute study [30] is comparable with the one of a 5G macro gNB. However, the maximum radiated power of the RF source in [30] is still three orders of magnitude higher than a 5G UE. As a result, we can conclude that none of the studies [28]–[30] adopt realistic P_{MAX} values for 5G UE, and only [30] imposes a value of P_{MAX} comparable to the one radiated by a 5G macro gNB.

Power Management. In this part, we shed light about the power management adopted by the studies [28]–[30] w.r.t. realistic 5G gNBs. In general, the power management of a RF source can be characterized according to two important aspects: *i*) how the power is spatially radiated over the service

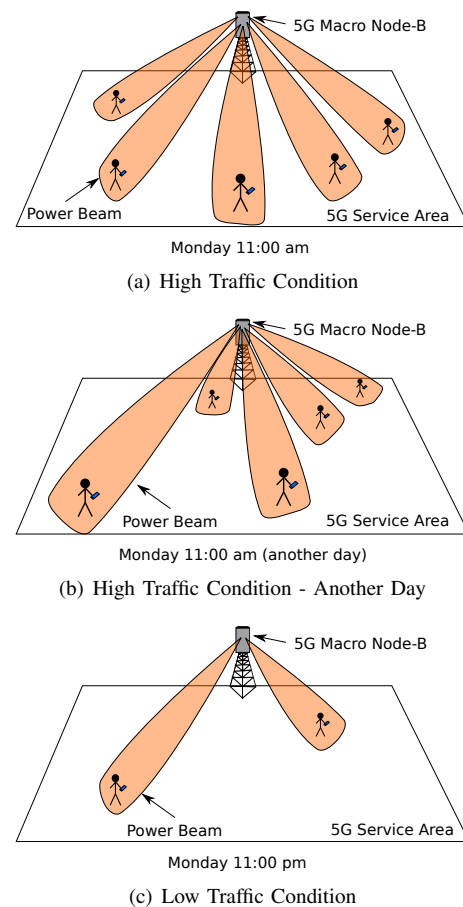


Fig. 8. Dynamic management of the radiated power for a 5G macro gNB. The power radiated over the territory varies in space and in time. For example, the same number of served users results into spatially different radiation patterns, as shown in (a),(b). The variation in the number of served users (e.g., between day and night) also impacts the radiation pattern, as shown in (a),(c).

area, and *ii*) how the power is varied across time. We denote *i*) as spatial power management, while *ii*) is referred to as temporal power management. Focusing on the spatial power management, the goal of [28]–[30] is to keep a uniform exposure for all the rats inside the room. This is achieved by adopting radiation patterns of the RF sources that tend to generate a uniform EMF in the chamber. In addition, the adoption of a torus structure in [30] and of the stirrers in [28], [29] allows to achieve this design goal. When comparing these features against the spatial power management performed by a 5G macro gNB, several notable differences emerge. As sketched in Fig. 8(a) a 5G macro gNB does not uniformly radiate the power over the service area. On the contrary, the radiated power tends to be focused into beams, which are directed to the 5G users. Therefore, the different zones of the service area do not receive the same amount of radiated power. Also, another important feature implemented in 5G gNBs is the ability to dynamically vary the power beams in accordance to the locations of the served users [81]. To this aim, Fig. 8(b) reports a scenario where the number of served users is the same as in Fig. 8(a), but with different positioning of the power beams, which then results in a different radiation pattern over the service area compared to Fig. 8(a). Consequently, we can

TABLE IV
24H AVERAGE RATIO OF RADIATED POWER δ^{ON} FOR THE DIFFERENT DEVICES.

5G Device	Value	Reference
RF source - NTP	0.38	[28], [29]
RF source - Ramazzini Institute	0.79	[30]
5G macro gNB	0.17	[83]
5G UE	0.17	4 [h] of usage per day [84]

claim that the approaches implemented in in [28]–[30] for the spatial power management are completely different w.r.t. the one pursued by a real 5G macro gNB.

Focusing then on the spatial power variations for a UE, the actual pattern radiated by the RF sources installed on the terminal depends on their physical positioning in the terminal, as well as the placement of other nearby elements such as screen, battery, photo-camera, and RF elements of other technologies (e.g., WiFi, Bluetooth, 2G/3G/4G). We refer the interested reader to [82] for a detailed overview of these aspects. In addition, the actual exposure depends on how the device is held (e.g., horizontally or vertically, with one hand or with two hands) [82], and thus can not be precisely known a priori. In any case, however, the design choices tend to avoid a radiation pattern directed towards the user [82], which is instead assumed in [28]–[30].

In the following, we concentrate on the temporal power management aspect, by first considering the comparison of [28]–[30] against a 5G macro gNB. As reported by [28], [29], the RF source is activated for 18 hours and 10 minutes per day, by imposing a repetition of an on period always followed by an off period, each of them lasting for 10 minutes. Since the goal of the studies [28], [29] is to keep a uniform exposure, the values of radiated power during the on period are almost constant.³ Let us denote with δ^{ON} the ratio of time over 24 [h] during which the radiated power is on. Consequently, we can claim that the average ratio of radiated power computed over the 24h is equal to 38% of the power radiated during the on periods, i.e., $\delta^{ON} = 0.38$. Focusing then on the Ramazzini Institute study [30], the RF source is continuously activated for 19 [h] over the 24 hours. Therefore, the 24h average ratio of radiated power is 79% of the power radiated during the on period, i.e., $\delta^{ON} = 0.79$. A natural question is then: Are these values meaningful when compared to the temporal power variation of a real 5G gNBs? To answer this question, we consider the realistic values of 24h average radiated power available for 4G networks, which we assume to be meaningful also for 5G equipment. As reported by [83], the 24h average ratio of radiated power from a 4G Node-B is at maximum equal to 17% when considering the whole set of Node-Bs deployed in the city of Milan (Italy). Although this percentage may appear pretty low at first glance, we remind that different previous works (see, e.g., [85], [86]) have demonstrated that 4G networks are subject to strong temporal and spatial traffic variations. For instance, the traffic varies across the hours of the same day (daytime vs. nighttime), the day of the week (e.g., weekday vs. weekend), and the location

³As reported by [28], [29], minor oscillations are possible in order to guarantee a uniform and stable SAR.

TABLE V
24H AVERAGE EMF $E_{(s)}^{24h}$ MEASURED IN THE NTP STUDY [28], [29] - GSM TESTS. THE MINIMUM EMF VALUE IS HIGHLIGHTED IN BOLDFACE.

Target SAR s	Frequency f	24h EMF $E_{(s)}^{24h}$
1.5 [W/kg]	900 [MHz]	56 [V/m]
3 [W/kg]	900 [MHz]	78 [V/m]
6 [W/kg]	900 [MHz]	111 [V/m]
1.5 [W/kg]	1900 [MHz]	48 [V/m]
3 [W/kg]	1900 [MHz]	68 [V/m]
6 [W/kg]	1900 [MHz]	98 [V/m]

of the 4G Node-Bs (residential vs. business districts). Since the amount of traffic managed by a 4G Node-B heavily impacts the radiated power, it is natural that the 24h average radiated power (expressed as a fraction of maximum power) is clearly lower than unity. In line with this trend, 5G is expected to adapt the radiated power w.r.t the time-varying traffic conditions wisely. For example, the number of power beams can match the number of users that need to be served, as graphically shown in Fig. 8(a)–8(c). Therefore, when the number of users is low (Fig. 8(c)), the 5G macro gNB can reduce radiated power. As a result, we can claim that the studies [28]–[30] adopt a temporal power management very conservative w.r.t. the one implemented by a 5G macro gNB.

We now focus on the comparison between the temporal power management in [28]–[30] w.r.t. the one implemented in 5G UE. First, we point out that the temporal variation of power depends on multiple factors, which include, e.g., the positioning of the UE w.r.t. the serving gNB as well as the channel conditions. For example, Non-Line of Sight (NLOS) conditions and distance from the serving gNB in the order of hundreds of meters may result in a non-negligible amount of radiated power by the UE [71]. In this context, we refer the interested reader to [88] for a detailed overview of the main communications features affecting the temporal variation of the RF output power. In addition, the temporal power management is heavily impacted by the type of applications (e.g., instant messaging vs. continuous downloading/uploading of photos/videos vs. continuous swapping of web pages enriched with multimedia content vs. notification-oriented applications), as well as the usage pattern of the user [89]. According to recent trends (see, e.g., [84]), the average usage of a UE is currently equal to 3 [h] per day, with a projected increase to 4 [h] in 2021. Even by assuming a worst-case scenario, in which the UE always transmits at full power during the whole usage time of 4 [h], the 24h temporal power variation is equal to 17%, i.e., a value clearly lower than the one imposed in the laboratory studies [28]–[30].⁴

ElectroMagnetic Field Exposure Levels. During this step, we shed light on the values of EMF imposed in [28]–[30], and their comparison against the estimated exposure from a 5G macro gNB. Focusing on the NTP studies [28], [29] the values of exposure are measured by EMF meters that are placed in the

⁴We remind that when a UE is not in use, the radiated power can be larger than zero due to, e.g., the App notifications and the pushing of multimedia content. However, the exposure zone tends to be different than the one during the active usage (e.g., a pocket vs. the front of the head and the chest).

TABLE VI
COMPUTATION OF THE EMF LEVEL AT A GIVEN DISTANCE FOR A 5G GNB.

Parameter	Notation	Value(s)/Formula	Comment and Reference
Operating Frequency	f	3.7 [GHz]	In use in Italy for the mid-band
Maximum Transmission Power	P_{MAX}	200 [W]	Value from real 5G equipment [79]
Statistical Reduction Factor	α_{STAT}	{0.25,1}	Value of 0.25 reported by [83]. Worst case value equal to 1.
Time-average Reduction Factor	α_{24}	{0.17,1}	Value of 0.17 for the city of Milan reported by [83]. Worst case value equal to 1.
Average Transmission Power	P_{AVG}	$P_{MAX} \cdot \alpha_{STAT} \cdot \alpha_{24}$	Computation done in [83]
Transmission Gain	G_{TX}	15 [dB]	Gain of a transmitting antenna based on [87]
Transmission Loss	L_{TX}	2.32 [dB]	Loss reported in [87]
Equivalent Isotropically Radiated Power	EIRP	$\frac{P_{AVG}[W] \cdot G_{TX}[\text{linear}]}{L_{TX}[\text{linear}]}$	Formula based on [87]
Normalized Antenna Numeric Gain	G_N	1	Worst case based on [87]
Free Space Wave Impedance	Z	377 [Ω]	Fixed parameter based on [87]
Distance from 5G gNB	d	2-100 [m]	Varying parameter
Sight Condition	-	Line of Sight (LoS)	Worst case assumption
EMF level at distance d	$E_{(d)}$	$\sqrt{\frac{EIRP \cdot G_N \cdot Z}{4 \cdot \pi \cdot d^2}}$	Point source model of [87]

chamber. More in depth, the average value of EMF exposure during the on period in each chamber and in each experiment is reported as raw data in the Appendix of the studies [28], [29]. Let us denote this value as $E_{(c,s)}^{ON}$, where c is the chamber index and s is the level of target SAR. Given $E_{(c,s)}^{ON}$, we initially compute the average 24 hours EMF in each chamber and for each SAR level. We denote this metric as $E_{(c,s)}^{24h}$. Intuitively, $E_{(c,s)}^{24h}$ allows to obtain a more conservative estimation of the level of exposure compared to $E_{(c,s)}^{ON}$. More formally, we have:

$$E_{(c,s)}^{24h} = \delta^{ON} \cdot E_{(c,s)}^{ON}, \quad [\text{V/m}] \quad (8)$$

Clearly, it holds that: $E_{(c,s)}^{24h} < E_{(c,s)}^{ON}$. Moreover, we point out that $E_{(c,s)}^{24h}$ is computed with a linear function of the EMF, although time-averaged EMFs are commonly evaluated by applying a root mean square. However, we remark that a linear average results into lower values of EMF compared to a root mean square, and thus allows to consider a very conservative scenario. In the following, we compute the average 24 hours EMF across all the chambers, denoted by $E_{(s)}^{24h}$, again computed for each SAR level s . $E_{(s)}^{24h}$ is formally expressed as:

$$E_{(s)}^{24h} = \frac{1}{|C|} \sum_c E_{(c,s)}^{24h}, \quad [\text{V/m}] \quad (9)$$

where $|C|$ is the total number of chambers used in the study. Similarly to Eq. (8), also $E_{(s)}^{24h}$ is conservatively computed as a linear average. The final values of $E_{(s)}^{24h}$ are reported in Tab. V.⁵ Interestingly, the 24 hours average EMF ranges between 48 [V/m] and 111 [V/m], depending on the experiment.

In the following, we focus on the EMF values of the Ramazzini Institute study [30]. Compared to [28], [29], the goal of [30] is not to target a certain level of SAR, but rather a given value of EMF, which is selectively set to 5 [V/m], 25 [V/m] and 50 [V/m]. By considering the daily activation period of the experiments, which we recall is equal to 19 [h],

⁵The table reports the value for the Global System for Mobile Communications (GSM) experiments. Similar values were obtained for the Code Division Multiple Access (CDMA) experiments, not reported here for the sake of simplicity.

we get the following values of 24 hours average EMF: 4 [V/m], 20 [V/m] and 40 [V/m].⁶

We then focus our attention on the 24 hours average EMF radiated by a 5G macro gNB. Let us denote with $E_{(d)}$ the EMF from a 5G macro gNB placed a distance d from the current position. Clearly, the value of $E_{(d)}$ is influenced by multiple factors (apart from d), including: the maximum transmission power of the 5G macro gNB, the presence of transmission gains/losses in the RF chain, the adopted power management schemes, the antenna gain and the sight conditions (e.g., LOS or NLOS). To this aim, Tab. VI reports the main steps to compute $E_{(d)}$, by adopting a set of conservative (and worst case) assumptions and realistic parameters. In brief, the maximum radiated power P_{MAX} is multiplied by the statistical reduction factor α_{STAT} and the time-average reduction factor α_{24} . These two factors are introduced to take into account the spatial and temporal power management performed by 5G macro gNB, and then obtain realistic values of the average radiated power P_{AVG} . Focusing on α_{STAT} , we refer the interested reader to [90] for a closed-form model to compute this parameter. In addition, recent studies in the literature (see e.g., [83], which is based on the IEC recommendations [91], [92]) suggest a value of α_{STAT} equal to 0.25. In this work, we consider two distinct values of α_{STAT} , namely 0.25 and 1. In this way, we are able to assess the impact of adopting either realistic or worst case settings. Focusing then on α_{24} , current works (see e.g., [83]) suggest that the 24h average variation of power is clearly lower than unity. However, also in this case we adopt two different values, namely $\alpha_{24} = 0.17$ and $\alpha_{24} = 1.0$, to consider both realistic and worst case assumptions. As a result, P_{AVG} is computed as $P_{MAX} \cdot \alpha_{STAT} \cdot \alpha_{24}$. In the following step, we compute the Equivalent Isotropically Radiated Power (EIRP), by scaling P_{AVG} with the transmission gain and losses reported in Tab. VI. Given the EIRP, we apply the point source model detailed by the ITU in [87] to finally compute $E_{(d)}$. It is important to remark that, compared to other models (reported in [87]), the point source represents a worst case, being the

⁶Similarly to Eq. (8), a linear average is computed also here, in order to obtain a set of conservative values.

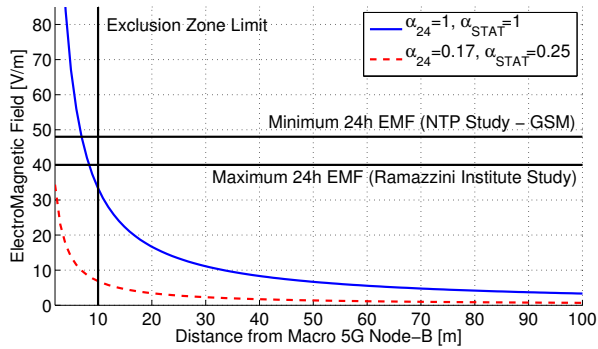


Fig. 9. EMF (electric field strength) vs. distance for different settings of a 5G macro gNB, based on the models and parameters detailed in Tab. VI. The setting with $\alpha_{\text{STAT}} = 1$ and $\alpha_{24} = 1$ represents the worst-case. The setting with $\alpha_{\text{STAT}} = 0.25$ and $\alpha_{24} = 0.17$ is based on realistic considerations. The figure highlights also the positioning of the tests performed by NTP and Ramazzini Institute and the typical size of an exclusion zone for a 5G macro gNB (figure best viewed in colors).

measured level of EMF exposure always lower than the one computed through this model in the far-field zone.

Fig. 9 reports the values of $E_{(d)}$ vs. the variation of d and the two values imposed for α_{STAT} and α_{24} . The figure also highlights the typical size of the exclusion zone with a vertical line, which we remind is the minimum distance between a user and a 5G macro gNB in LOS. In addition, the horizontal lines mark the maximum 24h average EMF imposed in the Ramazzini Institute study [30] and the minimum 24h average EMF measured in the NTP study [28], [29]. We select the maximum value for [30] because this is the only setting showing a statistically significant increase of critical diseases in the rats. On the other hand, we select the minimum EMF for [28], [29] since some adverse health effects were found even with this level of exposure.

Several considerations hold by observing Fig. 9. First, $E_{(d)}$ is rapidly decreasing with d , with values lower than 10 [V/m] when $d > 35$ [m]. Second, the introduction of realistic values for α_{STAT} and α_{24} results into an abrupt decrease of $E_{(d)}$, with an EMF lower than 10 [V/m] already inside the exclusion zone, and values lower than 5 [V/m] when $d > 20$ [m]. Third, the critical values of 24h EMF used in the studies [28]–[30] are clearly larger than the $E_{(d)}$ values outside the exclusion zone, even for the worst case $\alpha_{\text{STAT}} = 1$ and $\alpha_{24} = 1$. Fourth, when adopting realistic settings for α_{STAT} and α_{24} , $E_{(d)}$ is clearly lower than the minimum 24h average EMF of [28], [29] and the maximum 24h average of [30]. As a result, we can claim that the critical EMF levels used in [28]–[30] to argue the health impact from RF sources are never reached outside the exclusion zone of a 5G macro gNB. Therefore, the exposure levels for the general public are always far below the critical values of [28]–[30], thus ensuring safety for the population.

Finally, the analysis on the EMF exposure does not include the comparison against 5G UE. The near-field conditions at which such devices operate impose to consider the SAR metric, which is tackled in the next point.

Specific Absorption Rate Levels. We consider here the comparison of [28]–[30] in terms of realistic SAR values

for 5G UE. To this aim, Tab. VII reports the SAR values imposed by studies [28]–[30], and their comparison against the SAR of UE. Due to the limited number of 5G mobile devices, we include in our analysis also pre-5G UE with smartphone capabilities (whose data are retrieved from the publicly available database of [94]). In particular, by adopting the standardized procedures of [93], [95], two different SAR values are provided by each manufacturer of UE. The first one is referred to as a use case where the UE is close to the head during a call. The second one is instead representative for a UE worn on the body. The two average values, obtained over a wide set of UE models, are reported in Tab. VII. On the other hand, the NTP study [28], [29] adopts three different values of SAR over the whole animal body, corresponding to the different exposure levels imposed during the experiments. Similarly, three different whole-body SAR levels are employed in the Ramazzini Institute study [30].

Different considerations hold by analyzing the outcome of Tab. VII. First, the SAR values imposed by the NTP study are consistently higher than those of commercial UE. As a result, the negative outcomes of [28], [29] can not be generalized to UE. Second, the SAR values estimated from the Ramazzini Institute study are consistently lower than those of commercial devices. Therefore, the outcomes of [30] may be relevant to the UE in use (which we remind also include legacy technologies). However, we also point out that the measured SAR of UE is a local metric (i.e., not referred over the whole body), while the SAR of the animal-based studies [28], [29] is measured over the whole mass of the rats/mice. Therefore, the local and whole-body SAR values can not be directly compared, as they are referred to different absorption areas and volumes. We will shed light on this aspect when considering the SAR regulations in Sec. III. Intuitively, local SAR may be higher than whole-body SAR. However, it is also important to remark that the whole-body SAR of the animal-based studies [28], [29] are referred to rats, whose absorption area and volume are much lower compared to a human body. Eventually, the actual SAR levels of UE may differ from the values provided by manufacturers, since the SAR metric is influenced by multiple factors, which may introduce strong variations, as pointed out by ITU [88].

Transmission and Modulation Techniques. In this part, we focus on the different transmission and modulation techniques implemented in [28]–[30], and their comparison against the one adopted by real 5G equipment. Focusing on the NTP study [28], [29], the authors evaluate two different technologies, namely GSM and CDMA. Focusing on GSM, this technology leverages Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) techniques. More specifically, the GSM band is divided in frequency with channels of 200 [kHz]-wide; then, each channel is temporally divided into eight different time slots that are used for voice communications. During a voice call of a UE, a single time slot of a given channel is assigned to the terminal. The resulting signal shape is therefore clearly pulsed, as shown, e.g., in Fig. 2 of [28], [29]. Consequently, a large variation between average and peak power is observed. It is important to remark, however, that the useful metric

TABLE VII
COMPARISON OF SAR VALUES BETWEEN THE ANIMAL-BASED STUDIES [28]–[30] AND THE UE.

Device	Value(s)
RF Source - NTP Study [28], [29]	1.5 [W/kg] (whole body of the animal) 3 [W/kg] (whole body of the animal) 6 [W/kg] (whole body of the animal)
RF Source - Ramazzini Institute Study [30]	0.001 [W/kg] (whole body of the animal) 0.03 [W/kg] (whole body of the animal) 0.1 [W/kg] (whole body of the animal)
UE [94]	0.68 [W/kg] (local SAR measured by placing the UE close to the head during a call [93]) 0.98 [W/kg] (local SAR measured by wearing the UE on the body [95])

for the evaluation of exposure and/or SAR is the average power over the sequence of frames and not the instantaneous one. Eventually, [28], [29] adopted a Gaussian Minimum Shift Keying (GMSK) modulation scheme, which exploits a Gaussian filter to shape the digital data. Focusing then on the experiments based on CDMA, we remind that this technology employs the Direct Sequence Spread Spectrum (DSSS) transmission scheme, i.e., the information to be transmitted is firstly multiplied by a random code and then modulated on the carrier. Differently from GSM, each transmission employs the whole frequency band to transfer the information. In this case, a fundamental feature is the control of the emitted power, e.g., a UE should always transmit at minimum power to reduce the interference to the other terminals in the same cell. In addition, the adopted modulation scheme is Quadrature Phase Shift Keying (QPSK), which employs a phase change solution. The resulting implemented CDMA standard is Interim Standard 95 (IS-95).

Focusing then on the test conditions of [28], [29], the signals focused in the experiments are generated by a signal generator, with different uplink configurations, namely: one slot per frame active for GSM chambers, and the IS-95 standard uplink signal generator settings for CDMA chambers.⁷

In the following, we move our attention to the Ramazzini Institute study [30]. In line with [28], [29], also this work adopts FDMA and TDMA techniques, in combination with the GMSK modulation scheme. More in-depth, the authors of [30] state that a complete-time slot assignment and the call operating mode are exploited. Although the number of used slots is not explicitly reported, it is natural to assume that one slot per frame is active also in the study.

Lastly, we analyze the main features in terms of transmission and modulation techniques implemented in the 5G New Radio (5G-NR). Unless otherwise specified, we adopt the 3GPP release 16 specifications, whose working documents are publicly available in [96]. In order to support the variegated services offered by 5G, the features implemented in the physical layer are very flexible and highly customizable to the working conditions. More in-depth, the multiple access is realized with Orthogonal Frequency-Division Multiplexing (OFDM) with Cyclic Prefix (CP) in the downlink, and Discrete Fourier Transform-spread-Orthogonal Frequency Division Multiplexing (DFT-s-OFDM) or OFDM with CP in

the uplink. These techniques are the evolution of OFDM, which employs orthogonal subcarrier signals to transmit data information in parallel. Also, another great difference between 5G and legacy generations (like the one used in [28]–[30]) is the ability of employing a flexible (i.e., not fixed) subcarrier spacing. Eventually, 5G integrates the possibility of adopting different modulation techniques, which include Binary Phase Shift Keying (BPSK), QPSK, and Quadrature Amplitude Modulation (QAM).

In conclusion, the transmission and modulation techniques adopted in [28]–[30] are representative for legacy devices, which assume voice as the only service provided by the mobile network. On the other hand, the transmission and modulation techniques adopted in 5G devices are radically different, to cope with the great level of flexibility that this technology guarantees w.r.t. GSM or CDMA. This level of flexibility is clearly neglected by [28]–[30], thus posing limits on the applicability of their outcomes in the 5G context.

Summary. We have reviewed the works [28]–[30] under the perspective of 5G communications engineering. Many settings and/or assumptions imposed in [28]–[30] appear to be completely different and/or far from reality when compared to those ones adopted in 5G equipment. Such differences include:

- very short distances compared to the real ones from a 5G macro gNB;
- large amount of radiated power and almost absence of power management techniques;
- very long exposure times;
- very high EMF levels - much larger the ones radiated by a 5G macro gNB;
- whole-body SAR levels not directly comparable to local SAR in real smartphones;
- basic transmission and modulation schemes.

Therefore, it is not possible to claim that the health effects observed in [28]–[30] may appear in a real 5G deployment. To this aim, ICNIRP pointed out in a specific note [97] that the studies [28]–[30] do not provide a consistent, reliable and generalizable body of evidence for revising the exposure guidelines. Further studies, tailored to address the limitations of [28]–[30], are therefore needed.

2) Population-based Studies

We then review the population-based studies [46]–[51] from the perspective of the 5G communications engineering. To this aim, Tab. VIII compares the main communications features adopted in previous studies and how such metrics have to

⁷This information is available in [77].

TABLE VIII

COMPARISON OF THE MAIN COMMUNICATIONS FEATURES THAT ARE COLLECTED BY THE POPULATION-BASED STUDIES [46]–[51] W.R.T THE ONES THAT ARE MEANINGFUL IN THE CONTEXT OF 5G.

Feature	Population-Based Study	5G Communications
Evaluation	Questionnaire, Personal Interviews, Remote Interview, Mobile-operator Log	Cloud-based App, Mobile-operator Log
Evaluation Frequency	One shot, periodic	Continuous
Activity Type	Call	Call, Streaming Video, Social Media, Instant Messaging
Activity Intensity	Number of calls	Number of minutes spent for each App, Amount of content uploaded/Downloaded
Connectivity	Phone Number, Operator	Phone Number, Operator, Used Interfaces, Used Frequencies, Handover Information
UE position	Distance from head, Use of hands free devices	User Proximity, UE handling grasp
User location	Country, Residence	Country, Residence, Mobility Patterns
UE Information	Device Model	Device Model

be (eventually) changed or enriched when considering 5G equipment.

First of all, the evaluation in [46]–[51] is done by applying traditional ways, e.g., questionnaires, personal/remote interviews, and (in few cases) analysis of the log files made available by network operators. Due to the variegated set of 5G services, which include the exchange of data and voice communications, it is not possible to rely upon questionnaires and/or interviews to measure the UE activity. On the contrary, this information can be easily retrieved by running custom applications on the UE, which automatically transfer the measured data on a controlled cloud. Eventually, when this approach can not be pursued (e.g., due to privacy issues), log files made available by the mobile operators should be used.

Focusing on the evaluation frequency, the population-based studies [46]–[51] assume that the information about UE activity is retrieved with a small pace, i.e., either at the end of the considered period or on a periodic base. In contrast to them, 5G imposes continuous monitoring of UE activities, due to the highly temporal variation of the amount of data exchanged by the applications installed on the smartphone with the 5G services.

As a third aspect, the primary goal of the population-based studies is to monitor the duration of the calls. Although 5G still provides voice services, for which the call duration should be monitored, it is also important to report the time spent over each service type, which may include, e.g., streaming video, social media, and instant messaging. This step is fundamental to build a precise user profile, with exposure information for each service type. Besides, previous studies adopted the number of calls as an indicator of the intensity of UE activity. In the context of 5G, it is fundamental to track the amount of time spent in each application, as well as the amount of data uploaded/downloaded, to derive specific information tailored to the user and the adopted application(s).

Focusing on the connectivity, the population-based studies mainly measure basic features such as the subscriber mobile phone number and the mobile operator. In the context of 5G, this information has to be enriched by including the temporal usage of each interface(s) (e.g., 5G, 4G, WiFi). In addition, another important information includes the adopted frequencies (e.g., sub GHz, mid-band, mm-Waves), as well as the indication about the performed handovers (which can

affect the exposure patterns).

Focusing then on the UE position, the population-based studies [46]–[51] adopt simple metrics, like the distance from the head and the use of hands free devices. When considering 5G, it is essential to retrieve the proximity of the UE w.r.t the user, which can be from head/chest or other parts of the body. Besides, since the UE is used in different ways (e.g., talking, watching a video, texting, self-recording, environment recording), it is also fundamental to measure the UE handling grasp (e.g., one hand, two hands, vertical handle, horizontal handle). Eventually, the user location (in terms of country and residence) is used by population-based studies, e.g., to classify the users w.r.t. the living areas (e.g., urban, rural). In the context of 5G, user mobility is key information that should be also recorded.

Finally, population-based studies store the device model as UE information. Since the UE exposure varies across the different models, this information should be also recorded when considering 5G equipment.

Summarizing, although large efforts have been done by previous population-based studies [46]–[51] to assess the exposure from UE in legacy generation networks, their findings can not be entirely generalized also to 5G UE. Therefore, a new set of population-based studies, explicitly focused on 5G, should be put into place. This step would require to radically change the measurement techniques, the parameters that need to be measured, and the methodology to share the data. However, we point out all these steps are completely feasible from a technological point of view, even when considering currently available devices. Clearly, security and privacy issues should be carefully taken into account when considering the exchange of exposure information from UE, e.g., to avoid that malicious users inject misleading exposure information, thus making the health risk evaluation inefficient. We refer the interested reader to [102] for an overview of Blockchain-based solutions that may be put into place to secure 5G communications from/to UE.

III. 5G EXPOSURE: REGULATIONS AND COMPLIANCE ASSESSMENT PROCEDURES

A key aspect to minimize the health risks is the verification of compliance with regulatory limits. To face this point, we focus on the following aspects: *i*) analysis of the international

TABLE IX
PD LIMITS FOR FREQUENCIES f UP TO 300 [GHz].

PD	Metric	ICNIRP		IEEE C95.1		FCC-1997 [101]
		1998 [98]	2020 [25]	2005 [99]	2019 [100]	
Whole Body	Gen. Public	2 [W/m ²], 30 < f ≤ 400 [MHz]				2 [W/m ²], 30 < f ≤ 300 [MHz]
		$f/200$ [W/m ²], 400 < f ≤ 2000 [MHz]				$f/150$ [W/m ²], 300 < f ≤ 1500 [MHz]
		10 [W/m ²], 2 < f < 300 [GHz]	10 [W/m ²], 2 < f < 100 [GHz]	10 [W/m ²], 2 < f < 100 [GHz]	10 [W/m ²], 2 < f < 300 [GHz]	10 [W/m ²], 1.5 < f < 100 [GHz]
	Occupational	10 [W/m ²], 30 < f ≤ 400 [MHz]	10 [W/m ²], 30 < f ≤ 300 [MHz]	10 [W/m ²], 30 < f ≤ 300 [MHz]	10 [W/m ²], 30 < f ≤ 400 [MHz]	10 [W/m ²], 30 < f ≤ 300 [MHz]
		$f/40$ [W/m ²], 400 < f ≤ 2000 [MHz]	$f/30$ [W/m ²], 300 < f ≤ 3000 [MHz]	$f/30$ [W/m ²], 300 < f ≤ 3000 [MHz]	$f/40$ [W/m ²], 400 < f ≤ 2000 [MHz]	$f/30$ [W/m ²], 300 < f ≤ 1500 [MHz]
		50 [W/m ²], 2 < f < 300 [GHz]	100 [W/m ²], 3 < f < 300 [GHz]	100 [W/m ²], 3 < f < 300 [GHz]	50 [W/m ²], 2 < f < 300 [GHz]	50 [W/m ²], 1.5 < f < 100 [GHz]
Localized Exposure	Gen. Public	SAR Limits, $f < 10$ [GHz]	$0.058 \cdot f^{0.86}$ [W/m ²], 400 < f ≤ 2000 [MHz]	40 [W/m ²], 400 < f ≤ 3000 [MHz]	$1.19 \cdot f^{0.463}$ [W/m ²], 100 < f < 2000 [MHz]	SAR Limits, $f < 6$ [GHz]
		10 [W/m ²], 10 < f < 300 [GHz]	40 [W/m ²], 2 < f ≤ 6 [GHz]	18.56 · $f^{0.699}$, 3 < f ≤ 30 [GHz]	40 [W/m ²], 2 < f < 6 [GHz]	10 [W/m ²], 6 < f < 100 [GHz]
			$55/f^{0.177}$ [W/m ²], 6 < f ≤ 300 [GHz]	200 [W/m ²], 30 < f ≤ 300 [GHz]	$55/f^{0.177}$ [W/m ²], 6 < f < 300 [GHz]	
	Occupational	SAR Limits, $f < 10$ [GHz]	$0.29 \cdot f^{0.86}$ [W/m ²], 400 < f ≤ 2000 [MHz]	200 [W/m ²], 300 < f ≤ 3000 [MHz]	$5.93 \cdot f^{0.463}$ [W/m ²], 100 < f < 2000 [MHz]	SAR Limits, $f < 6$ [GHz]
		50 [W/m ²], 10 < f < 300 [GHz]	100 [W/m ²], 2 < f ≤ 6 [GHz]	$200 \cdot (f/3)^{1/5}$, 3 < f ≤ 96 [GHz]	200 [W/m ²], 2 < f < 6 [GHz]	50 [W/m ²], 6 < f < 100 [GHz]
			$275/f^{0.177}$ [W/m ²], 6 < f ≤ 300 [GHz]	400 [W/m ²], 96 < f ≤ 300 [GHz]	$274.8/f^{0.177}$ [W/m ²], 6 < f < 300 [GHz]	

guidelines defining limits on 5G exposure, *ii*) analysis of the impact of national regulations on the health risks, *iii*) overview of the policies to assess the exposure compliance of 5G equipment w.r.t the limits.

A. International guidelines on 5G EMF Exposure

The main international organizations defining guidelines on RF exposure are ICNIRP, IEEE and FCC. Both ICNIRP and IEEE revised the guidelines throughout the years. More in-depth, ICNIRP defined the EMF guidelines in 1998 [98], and then revised them in 2020 [25]. In a similar way, IEEE defined RF safety guidelines in the C95.1 standard, which was updated in 2005 [99], and then updated again in 2019 [100]. Finally, the FCC released the RF guidelines in [101], which, to the best of our knowledge, are still in force since their release, dated back to 1997. The reason for reporting various regulations of each organization is twofold. On one side, it is possible to track changes over the different guidelines and check whether the different guidelines are converging into a common set of limit values. On the other hand, different countries in the world implement different guidelines in their regulations [103]. For example, the ICNIRP 1998 guidelines [98] are still in force in many countries, with plans to gradually switch to the ICNIRP 2020 guidelines [25] in the forthcoming years.

In general, the EMF guidelines consider two distinct sets of limits for human exposure, namely general public limits and

occupational limits.⁸ The first set is tailored to the general public, who may be not aware of being exposed to radiation (e.g., EMF from gNB). On the other hand, occupational limits are defined for workers subject to RF exposure in a controlled environment, and therefore may take some precautionary procedures to reduce the exposure. A typical example of this second set is a technician performing a maintenance operation on a cellular tower under operation. The general public limits are, in general, more stringent than the occupational ones. In the following, we discuss the international limits in terms of PD, EMF strength, and SAR, under the 5G communications perspective.

As a side comment, the intrinsic temporal variability of 5G exposure requires to integrate in the national regulations also short-term exposure limits, which are e.g., defined in the ICNIRP 2020 guidelines [25]. We leave the discussion of this aspect as a future work, while in the rest of the section we concentrate on long-term limits (i.e., typically on time scales of several minutes).

1) PD Limits

We initially analyze the PD limits, shown in Tab. IX. For the sake of clarity, the table reports the limits without the averaging times. Several considerations hold by exploring the table values. First, a huge variability in terms of limits emerges, even by considering different versions of the same

⁸A further differentiation exists between basic restrictions and reference levels. In this work, unless otherwise specified, we consider the reference levels as the representative exposure limits.

TABLE X
EMF STRENGTH (INCIDENT E FIELD) LIMITS FOR FREQUENCIES f UP TO 300 [GHz].

Metric	ICNIRP		IEEE C95.1		FCC-1997 [101]
	1998 [98]	2020 [25]	2005 [99]	2019 [100]	
General Public	28 [V/m], $10 < f \leq 400$ [MHz]	27.7 [V/m], $30 < f \leq 400$ [MHz]	27.5 [V/m], $30 < f \leq 400$ [MHz]		27.5 [V/m], $30 < f \leq 300$ [MHz]
	$1.375 \cdot f^{0.5}$ [V/m], $400 < f \leq 2000$ [MHz]		Power density limits,		Power density limits,
	61 [V/m], $2 < f < 300$ [GHz]	Power density limits, $2 < f < 300$ [GHz]	$f > 400$ [MHz]		$f > 300$ [MHz]
Occupational	61 [V/m], $10 < f \leq 400$ [MHz]	61 [V/m], $30 < f \leq 400$ [MHz]	61.4 [V/m], $30 < f \leq 400$ [MHz]		61.4 [V/m], $30 < f \leq 300$ [MHz]
	$3 \cdot f^{0.5}$ [V/m], $400 < f \leq 2000$ [MHz]		Power density limits,		Power density limits,
	137 [V/m], $2 < f < 300$ [GHz]	Power density limits, $2 < f < 300$ [GHz]	$f > 400$ [MHz]		$f > 300$ [MHz]
Time	6 [min], $f \leq 10$ [GHz]	30 [min]	30 [min] (General Public)	30 [min]	30 [min] (General Public)
	$68/f^{1.05}$ [min], $f > 10$ [GHz] (f in GHz)		6 [min] (Occupational)		6 [min] (Occupational)

organization (e.g., ICNIRP or IEEE). Second, PD limits notably change across the frequencies, being some limits fixed for a given range of frequencies, and other ones varying with the adopted frequency. Third, the values of occupational limits are, in general, higher than the general public ones (as expected). Fourth, when going towards mm-Wave frequencies, most of the limits employ fixed values (i.e., not varying with frequency). Fifth, the latest versions of ICNIRP and IEEE adopt a common set of limits when the PD over the whole body is considered. Sixth, both the ICNIRP 1998 [98] and the FCC guidelines [101] enforce SAR limits (which are going to be detailed later on) for frequencies below the threshold when considering local exposure. Finally, PD limits for the local exposure are extensively defined for all 5G frequencies in the ICNIRP 2020 [25] and IEEE C95.1 guidelines [100].

2) EMF Strength Limits

We then move our attention to the limits on the EMF strength, which are reported in Tab. X. For the sake of clarity, the table reports the limits for the electric field, while the limits for the magnetic field are intentionally omitted. In general, these limits are enforced when considering the EMF from gNB. Interestingly, the latest versions of the limits define two working regions. In the first one, which is typically below 300 [MHz] of frequency, the limits are expressed in terms of maximum incident E field, with values very close among the different regulations. On the other hand, for very high frequencies (i.e., in the order of dozens of GHz), the limits are defined in terms of PD. For intermediate frequencies, ICNIRP 2020 [25] considers the maximum EMF strength up to 2 [GHz], then PD is taken into account for higher frequencies. Note that many countries in the world (see, e.g., the network limit map of [103]) still adopt the ICNIRP 1998 limits [98], which are instead defined in terms of the maximum incident electric strength for all the frequencies up to 300 [GHz]. Similarly to the PD case, general public limits are much more conservative than occupational ones (as expected). Finally, the table reports the minimum amount of time needed to measure the incident electric field. Interestingly, the last versions of ICNIRP [25] and IEEE C95.1 [100] guidelines converge to a 30 [min] of time duration for both general public and occupational. On the

other hand, the previous version of IEEE C95.1 [99], as well as the FCC guidelines [101], adopt a 6 [min] time duration when considering occupational exposure.

3) SAR Limits

In the final part of this step, we consider the SAR limits, which are reported in Tab. XI. We initially focus on the SAR to PD switching frequency f_{th} . In the context of 5G, f_{th} will differentiate between limits (and metrics) applied to mm-Waves w.r.t. the mid-band and the sub-GHz frequencies used by this technology. Interestingly, the values of f_{th} are not the same across the regulations. For example, the ICNIRP 2020 guidelines [25] do not impose any frequency threshold on the whole body exposure, and thus SAR-based limits are assumed over the whole range of 5G frequencies. However, a threshold $f_{th} = 6$ [GHz] is imposed for the local exposure, and this setting is in common with the FCC 1997 [101] and the IEEE C95.1 2019 [100] guidelines. Moreover, many countries in the world currently adopt the ICNIRP 1998 [98] and FCC 1997 [101] regulations, which enforce $f_{th} = 10$ [GHz] and $f_{th} = 6$ [GHz], respectively. In this case, PD-based limits will be enforced for mm-Wave frequencies.

Focusing then on the whole body SAR limits, we can note that the same values are used across the different regulations. In addition, both ICNIRP 2020 [25] and IEEE C95.1 2019 [100] adopt the same value of averaging time (i.e., 30 [min] for whole body exposure limits). Eventually, the averaging time for SAR in the FCC guidelines is set equal to the one defined in the IEEE C95.1 1991 standard [104]. Specifically, when considering occupational exposure, an averaging time equal to 6 [min] is assumed. When considering instead general public exposure, multiple times (reported in Table 2 of [104]) are defined, ranging however between 6 [min] and 30 [min] for the adopted SAR frequencies.

We then move our attention on the dose metrics for the whole body exposure. Clearly, SAR is always used for frequencies $f \leq f_{th}$. When considering instead $f > f_{th}$, different metrics are used (e.g., incident PD, SAR, plane-wave equivalent PD). However, it is important to remark that the ICNIRP 2020 guidelines [25] conservatively enforce SAR limits even for $f > f_{th}$ for whole body exposure limits.

TABLE XI
SAR LIMITS (INCLUDING DOSE METRICS) FOR FREQUENCIES f UP TO 300 [GHz].

Metric		ICNIRP		IEEE C95.1		FCC-1997 [101]	
		1998 [98]	2020 [25]	2005 [99]	2019 [100]		
SAR to PD Switching Frequency f_{th}		10 [GHz]	None (Whole Body) 6 [GHz] (Local)	3 [GHz]	6 [GHz]		
Whole Body	General Public	0.08 [W/kg]					
	Occupational	0.4 [W/kg]					
	Averaging Time	6 [min]	30 [min]	6 [min]	30 [min]	Defined in [104]	
	Dose Metric for $f \leq f_{th}$	SAR					
	Dose Metric for $f > f_{th}$	incident PD S_{inc}	SAR	incident PD S_{inc}	plane-wave equivalent PD S_{eq}	plane-wave equivalent PD S_{eq}	
Localized Exposure	General Public	2 [W/kg]				1.6 [W/kg]	
	Occupational	10 [W/kg]				8 [W/kg]	
	Averaging Time	6 [min]				Defined in [104]	
	Averaging Mass	10 [g]				1 [g]	
	Averaging Shape	Not defined	cubic				
		Dose Metric for $f \leq f_{th}$	SAR				
		Dose Metric for $f > f_{th}$	incident S_{inc}	absorbed PD S_{ab}	incident PD S_{inc}	epithelial PD	plane-wave equivalent PD S_{eq}

In the following, we consider the SAR limits for local exposure, reported on bottom of Tab. XI. In this case, ICNIRP and IEEE differentiate from FCC in terms of: limits, averaging time, and averaging mass. However, the latest versions of the regulations agree on a cubic mass, thus adopting a uniform metric. Focusing then on the dose metrics, the same consideration of the whole body exposure hold for $f \leq f_{th}$. When considering $f > f_{th}$, all the regulations adopt PD-based metrics. However, it is important to remark that the adopted PD metrics are not the same across the regulations. For example, the ICNIRP 1998 guidelines [98] adopt the incident PD, while the IEEE C95.1 2019 regulations [100] employ the epithelial PD (i.e., the power flow through the epithelium per unit area directly under the body surface). In this case, it is important to remark that custom PD limits (different from the ones reported in Tab. IX) are defined for the epithelial PD, i.e., 20 [W/m²] for $6 < f < 300$ [GHz] (general public) and 100 [W/m²] for $6 < f < 300$ [GHz] (occupational).

4) Summary

We have considered international guidelines that define exposure limits in terms of PD, EMF strength, and SAR. Although some efforts in making uniform rules across the different organizations obviously emerge, we can claim that 5G devices will be subject to different limits, due to the different frequencies at which they operate, as well as to the different thresholds and metrics used in the compliance assessment. This fragmentation may increase the health risks of 5G that are perceived by the population, since a lack of common limits and/or metrics may be (improperly) associated to a lack of a universal view among the different guidelines. Moreover, several countries in the world adopt more stringent exposure limits than the international ones, on the basis of precautionary principles. This issue, which notably complicates the health risks perception and the 5G deployment, is analyzed in detail

in the following subsection.

B. Impact of National Regulations

We provide a comprehensive review of the national EMF exposure regulations and their impact on 5G deployment. We divide our research under the following avenues: *i*) overview of national exposure regulations stricter than the ICNIRP 1998 [98] and/or FCC 1997 [101] guidelines⁹ (henceforth simply referred as ICNIRP and FCC, respectively), *ii*) impact of national regulations on 5G gNB deployment, *iii*) impact of national regulations on 5G UE adoption, *iv*) population-based analysis, and *v*) geographical analysis.

1) Overview of National Exposure Regulations Stricter than ICNIRP/FCC Guidelines

We preliminary perform an in-depth search of the exposure regulations in each country in the world. Our primary sources are the data made available by Global System for Mobile communications Association (GSMA) in [103], [105] and by WHO in [106], the work of Madjar [107], the report of Stam [108], the information retrieved from national EMF regulation authorities [109]–[112], and other relevant documents [113]–[121].

We initially focus on the national EMF regulations for gNB exposure. As a consequence, we focus on EMF strength with far field conditions. When a national regulation expresses the limit in terms of PD, we employ Eq. (4) to compute the EMF strength. In this way, we obtain a set of homogeneous limits.

Fig. 10 reports a graphical overview of the maximum EMF limits for different countries imposing strict regulations for

⁹We adopt the EMF limits defined in ICNIRP 1998 [98] and FCC 1997 [101] guidelines, as these regulations are currently still in force in many countries in the world. To the best of our knowledge, the adoption of the ICNIRP 2020 guidelines [98] by the national governments is an ongoing process, not yet completed at the time of preparing this work.

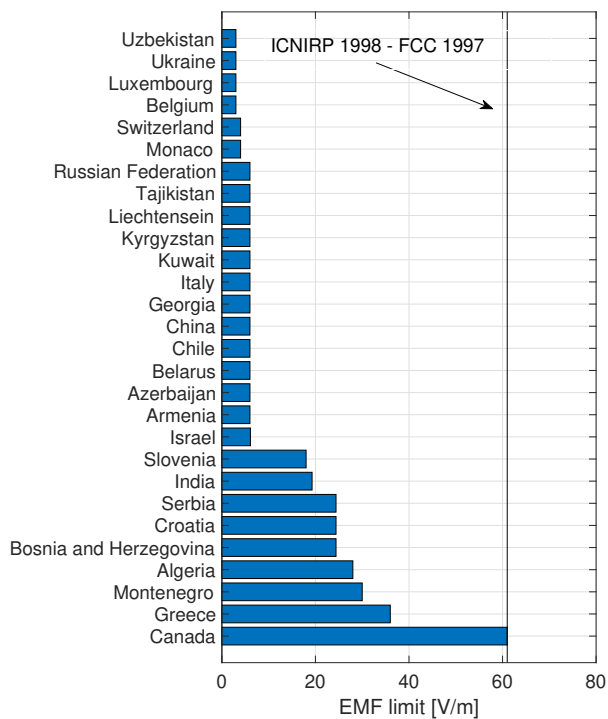


Fig. 10. Maximum 5G gNB limits on the field strength in residential areas for the countries adopting EMF regulations stricter than ICNIRP 1998 [98] and FCC 1997 [101] guidelines (frequency under consideration: 26 [GHz]).

gNB exposure, and their positioning w.r.t. the EMF strength limits of the ICNIRP/FCC guidelines.¹⁰ In this case, we report the limits by considering a 5G frequency equal 26 [GHz]¹¹ for multiple reasons, namely: *i*) this frequency is representative of the mm-Wave band in 5G, which triggers the highest exposure concerns from the population, *ii*) frequencies in the mid-band and sub-GHz bands are in general varying across the different countries (especially in the sub-GHz band); as a result, the EMF limit considerably changes w.r.t. the adopted frequency, making the comparison of the limits across the different countries a challenging task, *iii*) although not all countries in the world adopt the 26 [GHz] frequency in the mm-Wave band, the enforced limit does not generally vary across other frequencies in the mm-Wave band.

Several considerations hold by analyzing Fig. 10 in detail. First, a huge variability across the national limits apparently emerges. Second, when enforcing a limit stricter than ICNIRP/FCC, the reduction factor is considerably large, i.e., more than 10 times for the majority of the countries adopting strict limits. This reduction factor heavily impacts the installation of 5G gNBs in residential areas, as a strict EMF limit may be easily saturated in the presence of multiple operators and/or multiple technologies (e.g., 2G/3G/4G/5G)

¹⁰For the sake of simplicity, ICNIRP and FCC limits are collapsed in a single line. Moreover, a single limit is taken for those countries (e.g., Belgium) imposing different limits over different regions.

¹¹The EMF limits in Canada are stricter than ICNIRP 1998 [98] and FCC 1997 [101] guidelines only for 5G frequencies lower than 6 [GHz] [107]. When considering mm-Waves, like in this case, the EMF limits enforced in Canada correspond to the ICNIRP 1998 [98] and FCC 1997 [101] ones. However, we report Canada in the figure for completeness.

operating over the territory [15], [122]. Third, the perception of health risks connected to 5G gNB in countries with strict EMF limits may be higher compared to the ones enforcing ICNIRP/FCC limits, due to the fact that the measured EMF levels may be close to the limits.

We then move our attention on the national UE exposure regulations that are stricter than ICNIRP 1998 [98] and FCC 1997 [101] guidelines. Interestingly, the only countries in the world falling in this category are Belarus and Armenia, which still adopt regulations based on legacy Soviet Union limits, expressed in terms of maximum PD of 100 [QW/cm²] at an unknown distance. On the other hand, most of the other countries adopt ICNIRP/FCC limits, typically expressed in terms of SAR. Therefore, we can conclude that the perception of health risks connected to the adoption of 5G UE is typically lower than the gNB case.

2) Impact of National Regulations on 5G gNB Deployment

In the following, we jointly consider the impact of different EMF strength limits with the deployment of 5G gNBs in each country of the world. Specifically, we initially retrieve the information about 5G deployment in each country in the world, by considering nations that have already auctioned the 5G frequencies or have clear plans of forthcoming 5G auctions. Our primary sources are the GSMA documents about 5G spectrum management [123], [124], the European 5G Observatory [125] and other relevant (and up-to-date) national references [113], [115], [126]–[142].

We then consider the following taxonomy for the EMF limits: *L1*) stricter than ICNIRP/FCC, *L2*) ICNIRP-based, *L3*) FCC-based, or *L4*) unknown. Clearly, the deployment of the 5G gNBs will be a challenging step in countries with strict EMF limits (*L1*), a possible step in countries adopting ICNIRP/FCC limits (*L2,L3*), and an unknown step in countries without a regulation on the limits (*L4*).

Focusing then on the frequencies used by 5G gNBs, we consider the taxonomy in terms of 5G frequency bands that have been auctioned/planned in the country, and namely: *F1*) below 1 [GHz], *F2*) between 1 [Ghz] and 6 [Ghz], *F3*) above 6 [Ghz], *F4*) none. Each frequency in *F1*)-*F3*) has a different 5G performance target. The sub-GHz frequencies in *F1*) will be used to provide coverage, the mm-Wave frequencies in *F3*) will be exploited to guarantee capacity, while the mid band frequencies in *F2*) will provide a mixture of coverage and capacity. It is important to note that *F1*)-*F3*) are not exclusive, i.e., a country may exploit 5G frequencies of any combination of *F1*), *F2*), *F3*). For example, Italy will deploy 5G networks over frequencies in *F1*)-*F3*), while 5G frequencies in *F1*) and *F2*) are exploited in Saudi Arabia. Finally, a country is listed in *F4*) if the frequency plans for 5G have not been (yet) defined.

Fig. 11(a) reports the matrix of the possible combinations between adopted EMF strength limits (strict, ICNIRP, FCC, none) and planned/auctioned 5G frequencies (below 1 [GHz], between 1 [Ghz] and 6 [Ghz], above 6 [Ghz], none). Each cell in the matrix is identified by a group ID (between 1 and 16). Each cell's color is proportional to the number of countries belonging to the group (from white to red), whose value is also reported in the cell. Moreover, we stress the fact that each country may be repeated across the following frequency

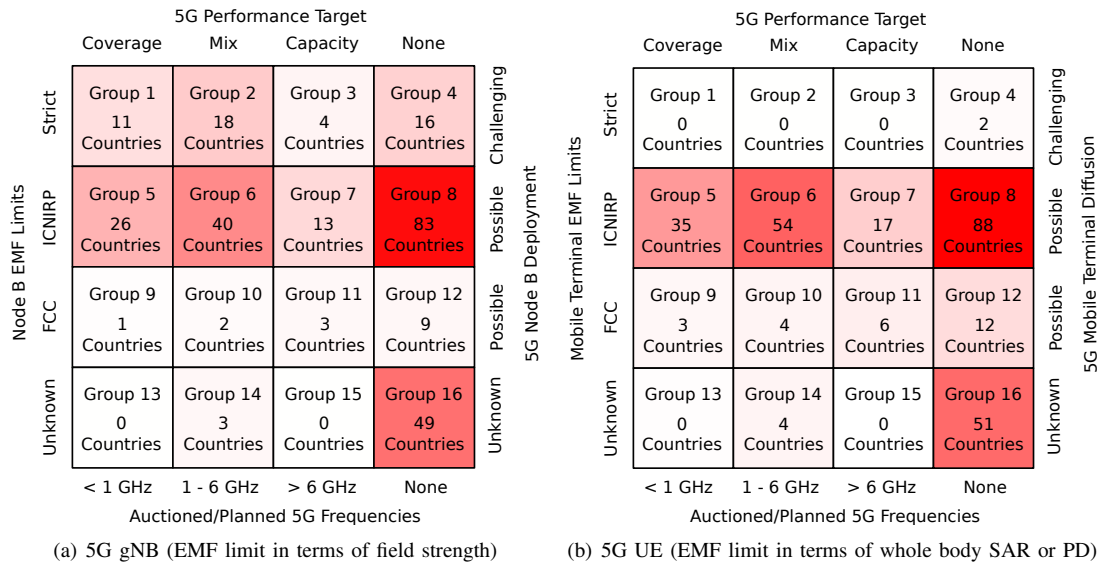


Fig. 11. EMF-limits / 5G frequencies matrices. Each cell in the matrix includes the group ID and the number of countries belonging to the group. The cell color is proportional to the number of countries belonging to the group, from white (zero weight) to red (weight equal to 88).

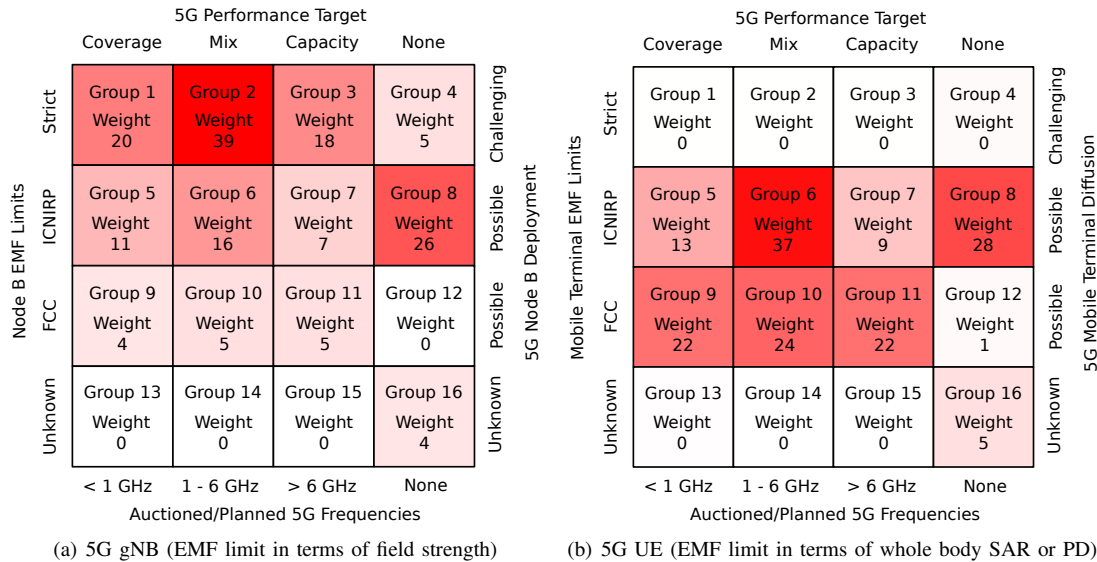


Fig. 12. EMF-limits / 5G frequencies matrices. Each cell in the matrix includes the group ID and the weight based on the population of each country belonging to the group. The cell color is proportional to the cell weight, from white (zero weight) to red (weight equal to 39).

options: below 1 [GHz], between 1 [Ghz] and 6 [Ghz], and above 6 [Ghz] (depending on the auctioned/planned 5G frequencies).

Several considerations hold by analyzing in more detail Fig. 11(a). First, as clearly shown by the intense red color of group 8, the majority of the countries adopt ICNIRP limits without any plan (so far) to deploy the 5G technology. Second, when observing the countries deploying 5G gNBs with ICNIRP limits (group 6), a typical setting is to target a mixture of coverage and capacity. Third, the highest health risks will be perceived in groups 1-3, i.e., the countries where 5G gNBs will be deployed under strict EMF constraints. Interestingly, the cardinality of groups 1-3 is not negligible. Fourth, the number of countries with unknown limits and without any 5G gNB implementation is also relevant (i.e.,

group 16). The population of these countries will perceive high health risks in case of future deployment of 5G networks. However, we also stress the fact that operators generally apply ICNIRP/FCC limits on a volunteer basis in countries without EMF limits.

In a nutshell, a considerable fragmentation emerges when the different EMF limits and the deployment of 5G gNBs are jointly considered. This fragmentation will also affect the perceived health risks associated with 5G in different countries.

3) Impact of National Regulations on 5G UE Adoption

We then move our attention to the impact of national regulations on the adoption of 5G UE. Similarly to the 5G gNB case, we consider the following taxonomy for the EMF limits: *L1*) stricter than ICNIRP, *L2*) ICNIRP-based, *L3*) FCC-based,

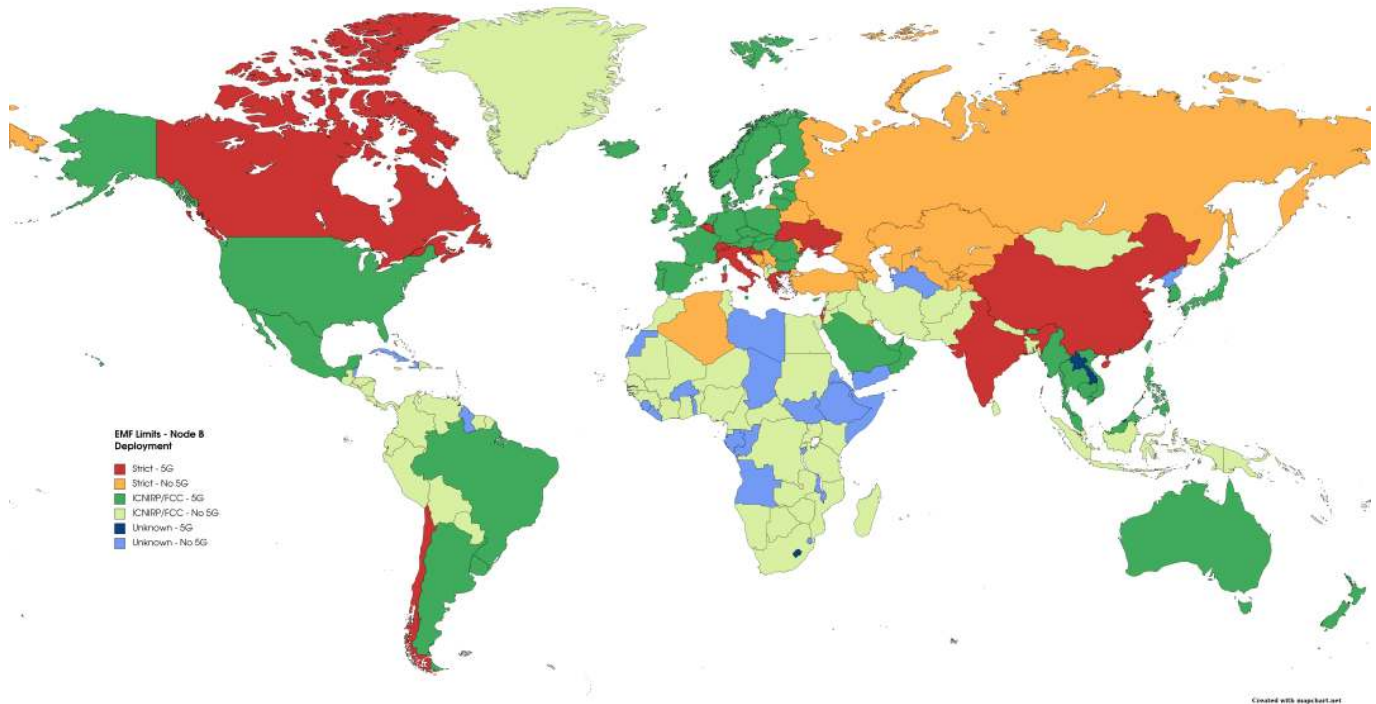


Fig. 13. World map with countries colored according to the EMF limits on field strength (strict, ICNIRP/FCC, unknown) and gNB deployment (5G, no 5G) - Most of micro states are omitted (Figure best viewed in colors) - data retrieved in June 2020.

or $L4$) unknown. Differently from 5G gNBs, in this case, we focus on the limits for UE expressed in terms of SAR and/or PD. In line with the 5G gNB analysis, we consider the same taxonomy (and same references) for the planned/auctioned 5G frequencies already used before, and namely: $F1$) below 1 [GHz], $F2$) between 1 [GHz] and 6 [GHz], $F3$) above 6 [GHz], or $F4$) none. Fig. 11(b) details the obtained matrix, with colors from white to red highlighting the number of countries falling in each group. By observing in more detail the figure, we can note that the group with the highest cardinality is composed of countries enforcing ICNIRP limits for the UE and no plans to adopt 5G devices (group 8). Moreover, we remind that the number of countries implementing strict EMF limits for UE is extremely limited in contrast to the 5G gNB limits reported of Fig. 11(a) (groups 1-4). On the other hand, the number of countries adopting ICNIRP/FCC limits with plans to exploit 5G UE is consistently higher compared to the 5G gNB case (groups 5-7, 9-11). Eventually, the number of countries with unknown limits and no plan to exploit 5G devices is not negligible (group 16), and similar to the 5G gNBs case.

In summary, the analysis conducted so far on UE reveals that there is a lower fragmentation of limits across the countries compared to the 5G gNBs case. While this condition will decrease the health risks perceptions associated to 5G UE, we need to remind that the number of countries without any plan to adopt 5G devices (with ICNIRP/FCC limits or with unknown limits) is very large.

4) Population-based Analysis

So far, we have conducted our analysis by counting the number of countries that fall within each group in the matrices of Fig. 11. However, a natural question emerges here: What is the

impact of each group when we consider the population in each country? To answer this interesting question, we have weighed each country by its population (in percentage w.r.t. the global population), and we summed up the weighed countries falling in each group. Fig. 12(a)-12(b) report the obtained matrices for the 5G gNB and UE cases, respectively. When the population weight is introduced for the 5G gNB case (Fig. 12(a)), we can note that almost 40% of the world population is living in countries where 5G is implemented as a mixture of coverage and capacity, under strict EMF limits (group 2). As a result, the perception of health risks associated to 5G gNBs will be extremely high in those countries. However, we can note that the percentage of people living in countries with 5G gNBs implementations under ICNIRP/FCC limits is not negligible (groups 5-7, 9-11). Eventually, 26% of the world population will be subject to ICNIRP limits, without any implementation of 5G gNBs (group 8). Finally, the percentage of people living in countries with unknown limits is overall pretty limited, i.e., lower than 5% (groups 13-16).

We then repeat the population-based analysis by considering the UE, as shown in Fig. 12(b). Interestingly, the outcome appears to be more homogeneous compared to the 5G gNBs population-based case (Fig. 12(a)) as well as the country-based analysis (Fig. 11). In particular, the percentage of people living in countries imposing ICNIRP/FCC UE limits and having plans to deploy 5G networks (groups 5-7, 9-11 in Fig. 12(b)) is predominant w.r.t. the unknown (groups 13-16) and strict cases (groups 1-4). In addition, we can note that, although the number of countries imposing FCC limits and exploiting 5G terminals appears to be limited (groups 5-7 in Fig. 11(b)), their population weight is very large (groups 5-7 in Fig. 12(b)),

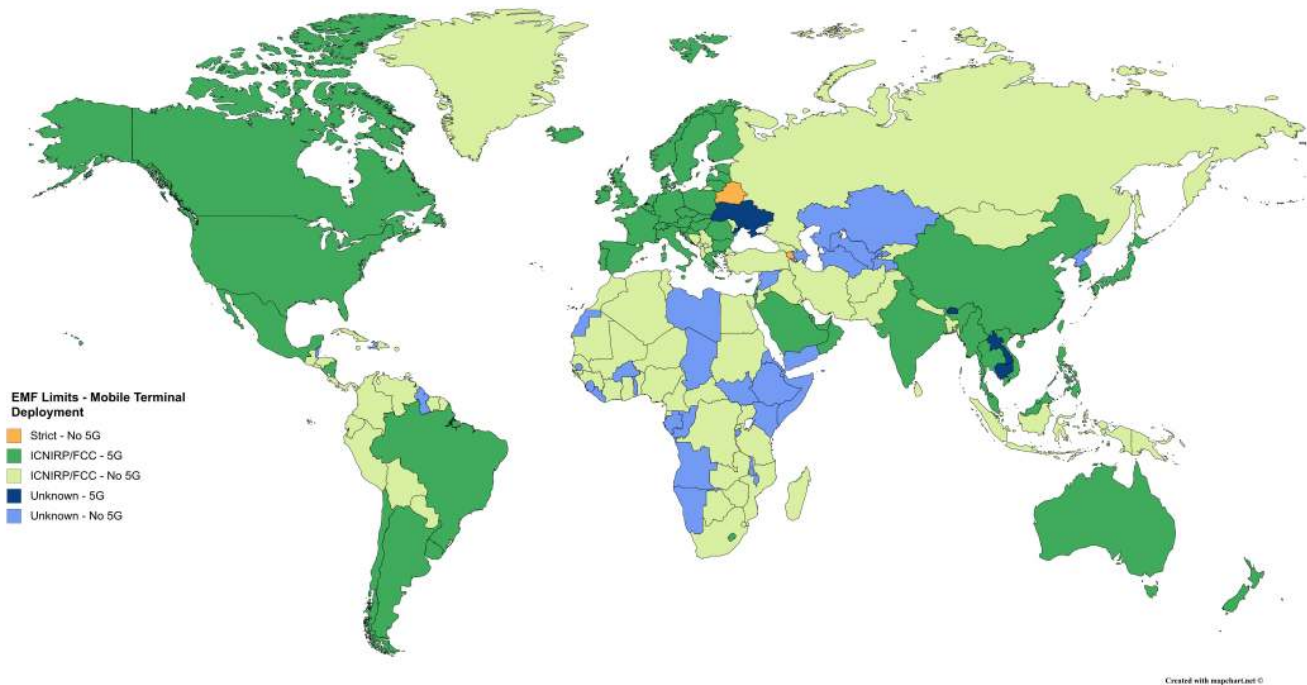


Fig. 14. World map with countries colored according to the EMF limits on SAR and/or PD (strict, ICNIRP/FCC, unknown) and UE deployment (5G, no 5G) - Most of micro states are omitted (Figure best viewed in colors) - data retrieved in June 2020.

i.e., always higher than 20% w.r.t the world population. As a result, we believe that the risk conditions (either perceived or potential) will be avoided for most of the population when considering 5G UE.

5) Geographical Analysis

In the following, we move our attention to the geographical fragmentation of EMF limits and 5G implementation at a country level. We initially focus on the 5G gNBs. To this aim, Fig. 13 reports the world map, by differentiating with different colors: *i*) countries enforcing strict EMF limits with 5G gNBs implementation (coral color), *ii*) countries enforcing strict EMF limits without 5G gNBs implementation (dark yellow color), *iii*) countries enforcing ICNIRP/FCC limits with 5G gNB implementation (dark green color), *iv*) countries enforcing ICNIRP/FCC limits without 5G gNB implementation (light green color), *v*) countries enforcing unknown EMF limits with 5G gNBs (dark blue color), and *vi*) countries enforcing unknown EMF limits without any plan of 5G gNBs deployment (light blue).

Several considerations hold by analyzing in more detail Fig. 13. First, most of the countries in Europe are deploying/have plans to install 5G gNB. However, the EMF limits notably vary across Europe, with different countries imposing strict limits and other countries enforcing ICNIRP/FCC limits. Second, a large number of countries previously included in the Soviet Union are still implementing strict EMF limits, without any plan to deploy 5G gNBs. Third, countries in the Mid East typically employ FCC/ICNIRP limits. However, the deployment of 5G gNBs is planned only in a limited subset of countries (e.g., Saudi Arabia, Oman, United Arab Emirates,

Qatar, and Djibouti). However, in this region, there are also countries enforcing strict EMF limits, e.g., Israel and Kuwait. Fourth, many countries in the Far East are planning to deploy 5G gNBs. However, a considerable variability in terms of EMF limits is experienced in these countries, being China and India enforcing strict EMF limits. Fourth, countries in Oceania generally enforce ICNIRP/FCC limits. Despite this fact, the implementation of 5G gNBs is limited to a subset of countries (e.g., Australia and New Zealand). Besides, we remark that the majority of the micro-states in Oceania (not reported in the map due to their limited land size) are applying ICNIRP/FCC limits without any 5G implementation. Fifth, many countries in Africa are enforcing ICNIRP/FCC limits. However, the number of states with unknown limits is far to be negligible. In any case, the implementation of 5G networks in this continent will be extremely limited. Sixth, Chile is the only country in South America with strict EMF limits. On the other hand, ICNIRP/FCC limits are widely adopted in this continent. Moreover, the deployment of 5G gNBs will be realized in different countries of the continent. Seventh, North America will implement 5G networks by applying ICNIRP/FCC limits. The only country imposing (slightly) stricter limits than ICNIRP/FCC is Canada.

Summarizing, the geographical fragmentation of EMF limits and 5G implementation clearly emerges when considering the deployment of 5G gNBs. Consequently, the fear of the associated health effects will be very different across different countries. The lack of 5G implementations, coupled with the fact that in many countries the EMF limits are still unset, is an obvious barrier for the deployment of 5G gNBs in the African

continent. On the other hand, the differences in terms of EMF limits in Europe, as well as in the Far East, will inevitably impact the deployment of 5G networks in these regions.

In the final part of our analysis, we consider the geographical fragmentation of EMF limits and 5G implementations when considering the UE. Fig. 14 reports the obtained outcome by adopting the same set of colors used in Fig. 13. By mutually comparing Fig. 14 against Fig. 13, we can see that the EMF limits for 5G UE are much more homogeneous across the world compared to the ones adopted by gNBs. Specifically, the ICNIRP/FCC limits on SAR and/or PD of the UE are adopted by most of the countries in the world. As previously pointed out, one exception is represented by Belarus and Armenia, which adopt UE limits stricter than ICNIRP/FCC. In addition, different countries in Africa and Asia do not adopt any limit, and they are not planning to exploit 5G UE. Therefore, the perceived health risks will be higher in such countries. In any case, we can conclude that the level of geographical fragmentation appears to be much more limited compared to the 5G gNBs case.

C. Compliance Assessment of 5G Exposure

We now review the main methodologies to perform the compliance assessment of 5G exposure w.r.t. the RF limits. We focus on the policies defined in the IEEE [143], [144] and IEC standards [91]–[93], [95], as well as in the ITU recommendations [87], [145]–[151] (complemented by supplements [88], [122], [152]), which assume ICNIRP 1998 [98] or IEEE C95.1 [99], [100] as underlying limits. However, we also point out that national regulations may impose specific rules for the compliance assessment of RF exposure. For example, in Italy, local municipalities often impose a minimum distance constraint between a site hosting RF equipment and a sensitive place (e.g., school, hospital, church). This constraint is additive w.r.t. national regulations and international guidelines. In this work, however, we concentrate on international guidelines for the compliance assessment, due to multiple reasons. First, since 5G is a relatively new technology, the local regulations may not include revisions of the assessment of compliance tailored to 5G equipment. Second, it is expected that the compliance assessment policies defined by ITU, IEC, and IEEE will be implemented in the national regulations in the forthcoming years.

In this context, a natural question arises: If the current regulations do not integrate the compliance assessment of 5G exposure, is it safe to install 5G equipment and to adopt 5G UE at present? The answer is affirmative: current RF limits are already defined for all the frequencies (including the ones used by 5G). Besides, current regulations for the compliance assessment can also be applied to 5G devices by introducing very conservative (and worst-case) assumptions, which always guarantee the population's safety. For example, the installation of 5G gNBs used for experimental trials in Italy is authorized by assuming an ideal maximum power that is radiated when all the beams are simultaneously activated in all the directions [83]. However, we stress the importance of revising the current regulations by considering the realistic

modeling and measurement of 5G features, to better assess the 5G exposure.¹²

Tab. XII overviews the main methodologies for the compliance assessment of 5G exposure. We divide the standards based on the following indicators: *i)* simulation-based procedures for 5G gNB, *ii)* simulation-based procedures for 5G UE, *iii)* measurement-based procedures for 5G gNB, and *iv)* measurement-based procedures for 5G UE. Clearly, the methodologies in *i)-ii)* can be applied during the planning phase of the 5G network and during the design of UE. On the other hand, the procedures in *iii)-iv)* are useful in order to assess the compliance of 5G networks under operation and/or already designed UE that have to be tested/monitored. In addition, the table reports a brief summary for each document, by detailing the features that are relevant to 5G exposure.

Several considerations hold by analyzing the methodologies in Tab. XII from the perspective of 5G communications engineering. First, IEEE define in [143], [144] the methodologies to assess the compliance of UE at both simulation and measurement levels. Specifically, the PD is taken as a reference metric, with a range of frequencies between 6 [GHz] and 300 [GHz]. Therefore, the procedures in [143], [144] are of high interest in the context of 5G communications, and in particular, for UE exploiting mm-Waves. Also, different UE positions (including the one in front of the head) are taken into account, thus matching the actual usage of UE during gaming, social networking, and video streaming. Second, the IEC standards [91], [93], [95] are focused on the assessment of compliance of 5G gNB and 5G UE. More in-depth, IEC 62232 [91] targets the assessment of compliance of SAR/PD and electric field strength from gNB, by considering approaches based on simulation and/or measurement of the exposure. In addition, the frequencies taken into account include mm-Waves (up to 100 [GHz]). Eventually, IEC 62232 [91] is complemented by IEC 62669 [92], which includes a set of representative case studies that implement the procedures of [91]. The document [92] is particularly relevant for the compliance assessment of 5G gNB exposure. For example, one case study is tailored to the compliance assessment of a 5G MIMO gNB. Moreover, different types of gNBs are taken into account (e.g., macro cells and small cells). Moreover, the procedures in [92] include the evaluation of PD in addition to SAR. Hence, they can be directly mapped to the corresponding PD-based limits defined by the international organizations for 5G gNB exposure. Focusing on the UE, the IEC 62209 documents [93], [95] detail the procedures for the compliance assessment of UE SAR. In this case, frequencies up to 6 [GHz] are considered (thus excluding mm-Waves). In line with the IEEE procedures [143], [144] different UE positions are taken into account by [93], [95]. However, in contrast to [143], [144], the considered metric is SAR (and not PD).

In the following, we move our attention to the ITU-T recommendations [87], [145]–[151], which are reported in the bottom of Tab. XII. In general, ITU-T provides brief documents, which can be used by the governments in order to build

¹²We refer the interested reader [83] for an overview of the modifications planned for the Italian country.

TABLE XII
COMPLIANCE ASSESSMENT METHODOLOGIES FOR 5G EXPOSURE.

Document		Assessment Methodology				Relevance for 5G Exposure
		Simulation-Based		Measurement-Based		
		gNB	UE	gNB	UE	
IEEE	P63195-1 [143]				Yes	<ul style="list-style-type: none"> - Reproducible and conservative measurement procedures of PD; - Multiple transmitters or antennas for UE; - Different UE positions (including in front of the face); - Frequencies from 6 [GHz] to 300 [GHz];
	P63195-2 [144]		Yes			<ul style="list-style-type: none"> - Conservative, repeatable and reproducible computation procedures of PD; - Multiple transmitters or antennas for UE; - Different UE positions (including in front of the face); - Frequencies from 6 [GHz] to 300 [GHz];
IEC	62232 [91]	Yes		Yes		<ul style="list-style-type: none"> - Procedures for determining the field strength and SAR in the vicinity of gNB; - RF source may be a single antenna or a set of antennas; - gNB frequencies up to 100 [GHz] are considered;
	62209 [93], [95]				Yes	<ul style="list-style-type: none"> - Procedures for measuring the UE SAR; - Frequencies up to 6 [GHz] are considered; - Different UE positions (including in front of the face);
	62669 [92]	Yes		Yes		<ul style="list-style-type: none"> - Case studies implementing the procedures detailed in IEC 62232 [91]; - Considered metrics include incident field, SAR and PD; - Different categories of gNB; - One case study includes a massive MIMO compliance assessment;
ITU-T	K.52 [145]	Yes			Yes	<ul style="list-style-type: none"> - Reference IEC 62232 [91] and IEC 62209 [93], [95]; - SAR methodologies up to 6 [GHz]
	K.61 [146]	Yes		Yes		<ul style="list-style-type: none"> - Reference IEC 62232 [91]; - Frequencies up to 300 [GHz] are considered.
	K.70 [87]	Yes				<ul style="list-style-type: none"> - Reference IEC 62232 [91]; - A simplified method for the calculation of the compliance distances (which takes into account also 5G) and an EMF software (which needs to be updated for 5G sites) are included.
	K.83 [147]			Yes		<ul style="list-style-type: none"> - Site evaluation procedures already include frequencies used by 5G equipment.
	K.91 [148]	Yes		Yes	Yes	<ul style="list-style-type: none"> - Based on IEC 62232 [91], IEC 62209 [93], [95]; - Frequencies up to 300 [GHz] are considered; - Typical sources of radiation do not include 5G; - Examples of real measurements do not include 5G equipment.
	K.100 [149]	Yes		Yes		<ul style="list-style-type: none"> - Conservative EIRP computation (applicable also to 5G gNB); - Introduced the idea of continuous monitoring of maximum transmitted power or EIRP; - Simplified assessment procedures covering frequencies up to 40 [GHz]; - Guidance to compute the power density for different technologies given selective measurements does not include 5G equipment.
	K.121 [150]	Yes		Yes		<ul style="list-style-type: none"> - General document integrating previous ITU-T K recommendations; - Useful as a starting reference for 5G operators and governments.
	K.122 [151]	Yes				<ul style="list-style-type: none"> - Useful for operators performing maintenance on the gNB; - Two sub-6 GHz frequencies are considered; - Two case studies based on point-to-point links exploiting frequencies comparable to mm-Waves are also reported.
	K Supplement 13 [88]				Yes	<ul style="list-style-type: none"> - Description of IEC 62209 [93], [95].
	K Supplement 14 [122]	Yes				<ul style="list-style-type: none"> - General discussion about the impact of EMF limits stricter than ICNIRP on the deployment of 5G networks.
K Supplement 16 [152]	Yes		Yes		<ul style="list-style-type: none"> - Based on IEC 62669 [92], IEC 62232 [91] and IEC 62209 [93], [95]; - Indications of future releases of relevant IEC documents are provided; - Compliance assessment tailored to 5G equipment. 	
Document		gNB	UE	gNB	UE	Relevance for 5G Exposure
		Simulation-Based Assessment		Measurement-Based Methodology		

national specific regulations for the compliance assessment of 5G exposure. For this reason, most of ITU documents refer to the IEC standards for the details about the compliance assessment procedures. Moreover, the ITU documents integrate the previous standards by: *i*) defining simplified installation procedures for gNB, based on different installation types [145], [149], *ii*) defining clear rules to differentiate between far field and near field exposure assessment [146], *iii*) proposing mitigation techniques to reduce the exposure in case the limits are not met [87], [145], *iv*) providing software and simplified models for the computation of the exposure in the different field regions [87], *v*) defining solutions to monitor the EMF levels [147], [149], with both broadband and frequency-selective measurements, *vi*) providing procedures to compute the actual maximum EIRP [149], which is then used in the compliance assessment procedures (e.g., the IEC ones), *vii*) providing high level views of the compliance assessment that may be useful for decision-makers [150] and *viii*) providing information for the assessment procedures in the vicinity of base stations [151] (which can be applied to workers operating on the site for maintenance operations).

Finally, we review the ITU-T supplements [88], [122], [152], which also include relevant information for the compliance assessment of 5G exposure. Specifically, K Supplement 13 [88] is tailored to the identification of the factors to determine the SAR from UE, based on IEC 62209-1 and -2. K Supplement 14 [122] is instead tailored to the evaluation of the impact of national limits stricter than ICNIRP and/or IEEE on the planning of 4G and 5G networks. In particular, strict regulations introduce several negative aspects, such as difficulty in using the full available spectrum, a limitation in the network densification, and a significant barrier to the technology innovation. Eventually, K Supplement 16 [152] is devoted to the compliance assessment of exposure from 5G gNB, by providing indications to the relevant IEC standards, as well as by including different case studies based on 5G (e.g., a massive MIMO gNB and a small cell).

Summarizing, different organizations (IEEE, IEC, ITU) provide guidelines (or draft of guidelines) for the compliance assessment of 5G exposure. Moreover, a great effort is currently devoted to the compliance assessment of exposure from gNB (with both simulation-based and measurement-based approach). When focusing on the UE, most of the approaches are based on SAR and PD measurement. Although revisions of different procedures (e.g., [148], [149]) are still needed to integrate case studies tailored to 5G, we can conclude that the compliance assessment of 5G exposure is overall already defined.

IV. HEALTH RISKS ASSOCIATED WITH 5G FEATURES

In this section, we analyze the health risks associated with key 5G features from the communications engineering perspective. Our goal is, in fact, not to survey the entire set of 5G features, but to concentrate on the ones that trigger health concerns among the population. More in-depth, we focus on the following controversial aspects:

- extensive adoption of massive MIMO and beamforming;

- densification of 5G sites over the territory;
- adoption of frequencies in the mm-Wave bands;
- connection of millions of IoT devices;
- coexistence of 5G with legacy technologies.

Since our goal is tailored to the communications engineering perspective, we consider health risks in terms of exposure generated by 5G gNB and by 5G UE. To this aim, Tab. XIII reports the considered 5G features, the corresponding aspects in the context of 5G communications, together with the relevant references. In the following, we provide more details about each feature and each work reported in Tab. XIII .

A. Extensive Adoption of Massive MIMO and Beamforming

We initially analyze the impact of massive MIMO and beamforming on the exposure from 5G devices. We focus on the following features: *i*) increase of power and number of radiating elements, *ii*) introduction of statistical exposure models, *iii*) measurement of exposure levels.

1) Increase of Power and Number of Radiating Elements

When considering 5G devices implementing MIMO and beamforming, two essential differences emerge w.r.t. legacy ones, and namely: *i*) a general increase in the maximum output power,¹³ and *ii*) an increase in the number of radiating elements. Focusing on the total power radiated by 5G gNB, data sheets of macro equipment available in the market report a maximum output power equal to 200 [W] [79]. On the other hand, 4G base stations typically radiate a consistent lower amount of power, e.g., in the order of 10-100 [W] [179].¹⁴ Therefore, a natural question arises: Is this increase of maximum power directly translated into an increase of exposure, and consequently, in an increase of the health risks? To answer this question, we need to recall how 5G gNBs will exploit MIMO. In fact, the MIMO technology is not new, and it has been in use for several years [153]. The main idea of MIMO is to exploit multiple antennas taking advantage of independent propagation paths to improve the transmission. With massive MIMO the number of antenna elements is radically increased (with a typical size of more than 64 elements) to further improve the system capacity.

In general, spatial multiplexing and beamforming are two key features implemented in 5G systems exploiting massive MIMO. As clearly detailed by [153], spatial multiplexing allows transmitting independent data over multiple uncorrelated paths. In contrast, beamforming allows concentrating the power of each antenna element on a specific user who needs to be served. Thanks to such features, the radiation pattern of 5G gNB is radically different compared to those of legacy technologies. In particular, the radiation pattern implemented by 4G base stations with MIMO is mostly static, i.e., with fixed beams over the territory. On the other hand, 5G gNBs exploiting massive MIMO adapt radiation patterns that are dynamically varied in space and time, i.e., to match the traffic

¹³Clearly, the maximum output power depends on the equipment class (e.g. macro cell vs. small cells), and therefore the maximum output power may be subject to strong variations.

¹⁴Clearly, deviations from these numbers are also possible for 4G base stations.

TABLE XIII
TAXONOMY OF HEALTH RISKS ASSOCIATED WITH 5G FEATURES AND RELEVANT ASPECTS IN THE CONTEXT OF COMMUNICATIONS ENGINEERING.

5G Feature	Relevant Aspects	References
Extensive adoption of massive MIMO and beamforming	Increase of power and number of radiating elements	[153]–[157]
	Introduction of statistical exposure models	[90], [158], [159]
	Measurement of exposure levels	[17], [153], [156], [160]–[163]
Densification of 5G sites over the territory	Computation of RF pollution at selected locations	[164]
	Computation of average received power	[165]
	Impact of strict EMF limits on densification	[71], [122]
Adoption of frequencies in the mm-Wave bands	Deployment status of mm-Waves	[157], [165]
	mm-Waves device exposure evaluation	[157], [166], [167]
Connection of millions of IoT devices	Maximum output power levels	[168], [169]
	Data-rate and delay requirements	[170], [171]
Coexistence of 5G with legacy technologies	Saturation levels of legacy pre-5G networks	[72], [172], [173]
	Impact of radio and TV broadcasting	[72], [174], [175]
	Interaction with weather satellites	[176]–[178]

conditions and/or the positioning of the users over the territory. Therefore, although the total power consumption of a 5G gNB is consistently higher than the one of a 4G gNB, the exposure exhibits a different pattern in time and space. As a consequence, the total power that is radiated by a 5G MIMO gNB is not spread over the entire coverage area, but it tends to be concentrated on specific portions of the territory and wisely modulated based on the network and traffic conditions. For example, according to [154] (and references therein), the current exposure from 5G gNB is four times lower than the maximum exposure in 95% of all cases. In any case, however, it is very unlikely that the whole power radiated by a 5G gNB will concentrate on a single beam with the maximum antenna gain for a time period sufficiently long, i.e., in the order of minutes. Therefore, despite the increase in the maximum radiated power of 5G gNB, the expected exposure from 5G gNB will be in line (and in general lower) compared to legacy technologies.

Eventually, the authors of [155] present a numerical approach for assessing the exposure of massive MIMO gNB in indoor environments, by combining a ray-tracing technique and the time-domain method to estimate the SAR on a phantom. The authors then compute the maximum power admissible for a 5G gNB to ensure that the estimated SAR is below the ICNIRP limit of 2 [W/kg] at a distance of 8 [m]. Interestingly, the maximum power per antenna is at most equal to 110 [W] in the worst scenario. However, since the considered environment is an indoor scenario, the 5G gNB can be implemented with a small cell (and not with a macro one), thus being able to employ an output power consistently lower than the maximum values extracted by the authors. Therefore, the perceived health risks are minimized in this case.

In parallel with the increase of power, another aspect that characterizes 5G devices is the increase in the the number of radiating elements. In general, the size of 5G gNB tends to be larger than that of legacy technologies, due to the need to host the circuitry to power the antenna elements [156]. Although this aspect is not a problem in cellular deployments (especially for roof-mounted and poles installations), the increase of size may be associated to a higher exposure. Focusing on 5G UE, it is expected that multiple antenna elements (up to 8) will be

exploited by terminals implementing full 5G functionalities [157]. However, no change in the size of the UE is planned. Therefore, the expected impact on the user side in terms of perceived health risks will be marginal.

2) Introduction of Statistical Exposure Models

Traditional methods to estimate the exposure from base stations are based on very conservative assumptions, including maximum transmission power and static beams in all the covered area directions. Although such assumptions are, in general, valid for legacy technologies, they tend to be overly conservative when considering 5G gNB [158]. In general, the application of conservative assumptions to estimate the exposure from 5G gNB is detrimental for the health risks due to two main reasons. On one side, the exclusion zone of each 5G gNB tends to be very large, i.e., in the order of several dozen meters [78]. On the other hand, the predicted exposure levels tend to be pretty high [78], thus triggering health concerns by the population. Therefore, the exposure estimation of 5G gNB is based on the introduction of statistical models [90], [158], [159], which allow on one side to better assess the size of the exclusion zone of the gNB, and on the other one to estimate the predicted exposure levels over the territory in a more realistic way.

In this context, [90] introduces a statistical model to take into account multiple factors, such as the gNB utilization, the time-division duplex, the scheduling time, as well as the spatial distribution of the users in the covered area. Results show that, by applying the presented model, the largest maximum power is less than 15% w.r.t. the corresponding theoretical one. Consequently, the exclusion zone can be reduced by a factor of 2.6 compared to a traditional methodology. Similarly, [158] presents a statistical approach by leveraging on the three-dimensional spatial channel model standardized by 3rd Generation Partnership Project (3GPP). Results show that the exclusion zone of a massive MIMO gNB, computed through the statistical model, is reduced by half compared to the ones obtained by a traditional approach (i.e., not based on statistical parameters). Eventually, the authors of [159] compute the probability that multiple antenna elements of 5G massive MIMO gNB are radiating with the actual maximum power over the same point of the territory and at the same time.

Results show that the probability of this event is clearly lower than the case with a single antenna element.

In summary, the high dynamicity introduced in power radiated by 5G gNB implementing MIMO and beamforming imposes to consider statistical models to more realistically compute both the exposure levels and the size of exclusion zones compared to traditional approaches. This step could be beneficial to reduce the health risks perceived by the population.

3) Measurement of Exposure Levels

A third aspect that has to be considered is the measurement of exposure levels due to the large adoption of MIMO and beamforming features. Focusing on gNB, the authors of [17] point out that the methodologies used to measure the exposure in legacy networks are not always suitable for assessing the exposure of 5G gNBs exploiting massive MIMO and beamforming. In general, such features may cause uncertainties in the estimation of the field strength, according to [160]. This aspect may be an issue for the health risks that are perceived by the population. However, as also suggested by [160], a possible solution could be to force the system to generate a maximum toward the direction of the measurement position. Obviously, this step requires either to position one or more UE in the vicinity of the measurement probe and/or to perform the measurement in cooperation with the operator owning the 5G gNB.

In general, the measurement procedure of 5G gNB involves either wide-band probes operating on a given range of frequencies, or narrow-band probes that are able to retrieve information on the field strength on a set of selected frequencies. Focusing on the former methodology, the authors of [161] measure the output power levels of a 5G gNB, by exploiting massive MIMO in an operational network. Interestingly, the time-averaged power transmitted on a given beam direction is lower than the maximum theoretical output power. In addition, the maximum field strength measured in the proximity of the 5G gNB represents a tiny fraction (lower than 6%) compared to the one that is estimated by assuming a maximum power transmission. In line with [161], the authors of [153] perform a measurement campaign of the field strength of a 4G base station implementing massive MIMO. Although the considered base station belongs to legacy technologies, the measured exposure levels are meaningful in the context of 5G, thanks to the adoption of massive MIMO in the considered scenario. The obtained results demonstrate that, even when the base station is fully loaded, the measured field strength is a small ratio (lower than 17%) compared to the maximum ICNIRP limit for occupational exposure. Therefore, both the works [153], [161] indicate exposure levels lower than the theoretical ones, and in general lower than the limits. Although further assessments are required (e.g., by extending the measurement to other operational networks and to different traffic conditions), current results indicate that the exposure from gNB implementing massive MIMO will be overall limited, thus minimizing the overall risks for the population.

In the following step, we focus on the assessment of exposure through narrow-band measurements. More in detail, [162] aims at identifying the Synchronization Signal Block,

in order to assess the power density carried by its resources and to finally extrapolate the theoretical maximum exposure level. The authors consider a location at around 60 [m] from the 5G gNB (in LOS conditions), at a close distance (around 7 [m]) from the UE. Also, a constant fixed beam, oriented towards the position of the UE, is enforced at the 5G gNB site. Interestingly, the measured exposure is at most equal to 3.716 [V/m] in the worst case (achieved by imposing a 100% of downlink traffic load). By applying the methodology detailed in IEC 62232 [91], a theoretical maximum field strength of 5.537 [V/m] is obtained. It is important to remark that this value is lower than the maximum limit for countries adopting ICNIRP/FCC-based regulations (see Tab. X), and thus being able to limit the health risks perceived by the population. On the other hand, this value is very close or above the maximum limit for different countries imposing regulations stricter than ICNIRP/FCC (reported in Fig. 10). Clearly, in such countries, the associated health risks of 5G gNB deployments similar to [162] may be highly perceived by the population.

Moreover, the authors of [163] point out that the maximum EMF level in a given location is a combination of three factors, namely: *i*) the total number of subcarriers of the carrier, which depends on the signal bandwidth and the numerology, *ii*) the fraction of the signal frame reserved for downlink transmission, *iii*) the maximum EMF level measured for a single resource element, which in turns depends on different other metrics (including a factor depending on the serving beam). Interestingly, the importance of adopting UE forcing full load traffic in the vicinity of the measurement point is stressed by the authors. Eventually, the authors of [156] define the experimental procedures for estimating the relevant factors associated with time division duplexing and beam sweeping, which are then used to extrapolate the maximum field strength from the exposure measurements.

Summarizing, current works tailored to the measurement of the incident EMF field strength from 5G gNB exploiting MIMO and beamforming reveal that the overall exposure is limited and in general lower than the maximum theoretical values. Although further efforts are needed, e.g., to extend the outcomes by measuring the EMF over different operational networks and different traffic conditions, the current literature indicates that the health risks from exposure can be minimized. However, we stress the fact that the measured EMF is highly influenced by the traffic and the user activity in the proximity of the measurement probe. Therefore, it is of fundamental importance to setup a proper (and meaningful) measurement scenario.

B. Densification of 5G sites over the Territory

A second controversial aspect among the population is that the pervasive installation of 5G gNBs over the territory results in an exponential increase of exposure, thus leading to an unacceptable increase of the health risks. The closest works investigating this issue from a scientific point of view are [164], [165]. More in detail, the authors of [164] develop a very simple model to evaluate the RF pollution (in terms of total

received power) at selected locations of the territory (i.e., at an average or a minimum distance from the serving gNB). A set of closed-form expressions are then derived from the model, to evaluate the increase/decrease of RF pollution among a pair of candidate gNB deployments that are characterized by different gNB densities over the same service area. By leveraging on a set of worst-case and common assumptions (which include, e.g., a homogeneous set of gNB of regular size, maximum radiated power, and simultaneous activation of all the beams by each gNB), the authors demonstrate that, when a given performance level has to be ensured (e.g., in terms of minimum received power), the densification of the 5G network allows to promptly reduce the RF pollution. This result can also be explained in a very intuitive way: in a network with a high density of gNB, each site has to cover a small service area, and hence the required output power can be limited. On the other hand, a network composed of few gNB is characterized by a huge coverage area for each site, and hence higher radiated power. Therefore, in contrast to the common opinion of the population, the increase in the number of 5G gNBs allows to reduce the exposure at the selected locations (i.e., at an average distance or a minimum one from the serving gNB). Eventually, the authors of [164] considers a scenario where the minimum received power *and* the number of 5G gNBs are jointly increased, showing that, even in this case, the RF pollution estimated at the selected locations is limited.

The outcomes of [164] are further corroborated by [165], in which the authors evaluate the average received power over a whole territory and a set of candidate deployments. Results demonstrate that the average received power is dramatically reduced when the number of 5G gNB is increased. Consequently, the associated health risks are minimized. Moreover, another aspect that can be observed from the network densification considered in [164] is the harmonization of exposure. When a network is composed of few gNBs, the users in close proximity to the sites tend to be exposed to higher levels of exposure compared to the ones that are far from the gNB. On the other hand, when the number of gNB is increased, the exposure tends to be more uniform over the territory. This issue is usually neglected by the population and may have a significant impact on the perceived health risks.

In any case, however, it is essential to remark that the densification of the network is impacted by the EMF regulations, which tend to limit the installation of 5G gNBs over the territory. This is especially true in countries adopting exposure limits stricter than ICNIRP/FCC [122], for which the installation of 5G gNB is prevented, e.g., in proximity to sensitivity places and/or in the presence of other RF installations. Although this aspect may appear beneficial for the health risks at first glance, the actual exposure levels are negatively impacted by strict regulations. To this aim, the authors of [71] perform a broad set of exposure measurements in a 4G operational network that is deployed under very strict regulations. Results show that strict regulations limiting the installation of 4G base stations have a negative impact on the exposure levels generated by UE and on the performance perceived by users. In particular, the lack of 4G base stations in the neighborhood under consideration forces the UE to

be served by base stations that are typically far (i.e., more than 1000 [m]) and in NLOS conditions. This issue results in a large electric field activity generated by the UE and poor performance levels in terms of low throughput and large amount of time to transfer data in the uplink direction.

C. Adoption of Frequencies in the mm-Wave bands

The third controversial aspect triggering concerns by the population is the adoption of mm-Waves in 5G. To this aim, we remind that the biological impact of mm-Waves have been studied in the past years, although not in the context of cellular communications (see e.g., [180]–[185]). However, previous works investigating the health impact of mm-Waves did not find any adverse effect for exposure below the limits enforced by law. A similar observation is also reported by WHO [186]. Moreover, the same organization is currently conducting a health risk assessment of exposure over the entire range of RF range (including mm-Waves), which will be completed by 2022 (i.e., in parallel with the deployment of the 5G networks). This step would be beneficial to reduce the health risks of 5G that are perceived by the population. However, we point out the current lack of well-done biomedical studies focused on the assessment of (potential) health effects from 5G devices operating on mm-Waves.

In the following, we move our attention to radio communications from 5G gNBs exploiting mm-Waves. In general, such devices will be installed in scenarios where very high capacity is required [187]. However, it is important to remark that mm-Waves are subject to very large path losses compared to micro-waves [188]. Also, other effects, including, e.g., low penetration capabilities inside the buildings, severely impact the maximum distance between a gNB and a UE operating at these frequencies. As a consequence, 5G deployments exploiting mm-Waves will be mainly realized through micro and small gNB, which will be placed in close proximity to the service area [187]. This, in turn, naturally limits the scope of application of mm-Waves, which will be not deployed on the whole territory, but rather at traffic-demanding hotspots (e.g., airports, stadiums, shopping malls). However, it is also important to remind that 5G will be mainly realized with sub-GHz and sub-6 [GHz] in many countries in the world, and thus already limiting the exploitation of mm-Waves in the near future. For example, in Italy, the operators are not subject to any coverage constraint over the mm-Wave frequencies, while strict coverage constraints for lower 5G frequencies are required [165]. As a result, the auction on 5G frequencies in Italy resulted in a large competition among the operators over sub-6 [GHz] frequencies, while a very limited competition was observed for mm-Waves. Moreover, current international guidelines and current compliance assessment procedures already hold for mm-Waves, thus ensuring health risk minimization. However, we need to point out that measurement studies, tailored to the assessment of exposure of 5G gNB, are needed, in order to limit the perceived health risks by the population.

In the following part of our work, we focus on the exposure from UE with mm-Waves. According to [157], 5G devices

exploiting mm-Waves will be not realized with a very large number of antenna elements, being 4-element or 8-element antenna arrays the most promising solutions. However, previous works (e.g., [189]) consider the design of UE with antenna arrays composed of a larger number of radiating elements. Interestingly, the authors of [157] demonstrate that the minimum peak EIRP of a 5G UE with mm-Waves satisfies both ICNIRP, FCC and IEEE exposure limits. In addition, the authors of [166], [167] point out the importance of evaluating the PD in proximity to 5G UE with mm-Waves, claiming that a traditional approach based on magnitude-based field combination may led to very conservative estimation of the peak spatial-average PD. Moreover, a more accurate PD assessment, based on the magnitude and phase of the EMFs, is advocated.

D. Connection of Millions of IoT Devices

A fourth controversial aspect among the population is the effect on exposure due to the huge number of 5G terminals that will be pervasively connected in the same area. In this context, a common opinion is that massive deployments of IoT terminals connected through 5G networks will result in an unacceptable and continuous exposure for users. To this aim, we analyze the problem from the perspective of the communications engineering by reporting a set of evidences, summarized as follows. First, current specifications defined by 3GPP always impose very low values of maximum transmitted power for each terminal, even for 5G ones [168] (i.e., generally at most equal to 23 [dBm] in the majority of the cases, and in any case no higher than 35 [dBm]). Second, when considering IoT terminals, more stringent power requirements may be introduced [170], in order to reduce the consumption and to increase the battery lifetime, in line with goals of Low Power Wide Area Networks architectures [190], [191]. For example, typical values range between 23 [dBm] and 14 [dBm] [169]. Third, international guidelines always impose maximum SAR and/or PD values to control the exposure from the terminals, thus guaranteeing safety for the population. Fourth, even in the presence of millions of terminals in the same area, the distance between the user and the terminal(s) will play a major role in determining the exposure. For example, when the distance is in the order of (few) meters, the exposure will be negligible, due to the aforementioned very limited maximum output power generated by the terminals. Also, the level of exposure may be further reduced due to the presence of obstacles, e.g., walls in the proximity of the terminals. Fifth, IoT communications are in general very different compared to human communications [170], [171]. In most of the cases, IoT devices will need to communicate with the rest of the world at a small pace, with a limited data rate, and with pretty large delays compared to human-centered communications. This will be translated into extremely low power levels in the uplink directions, and consequently in very low levels of exposure.

E. Coexistence of 5G with Legacy Technologies

The last concern triggering health risks from the population is the coexistence of 5G with legacy technologies. We analyze

the problem from the perspective of communications engineering, under the following avenues: *i*) saturation levels in pre-5G networks (i.e., 2G/3G/4G), *ii*) impact of radio and TV broadcasting, and *iii*) interaction of 5G with weather satellites.

1) Saturation Levels of Legacy pre-5G Networks

As reported by ITU [122], the installation of 5G sites is a challenging step in countries adopting EMF regulations stricter than ICNIRP/FCC guidelines. The main effect that is observed is the saturation of EMF levels to the maximum limits, especially in urban zones served by multiple operators and by multiple cellular technologies. In the presence of a saturation zone (i.e., a portion of territory in which the total exposure is already close to the limit defined by law), the deployment of new 5G gNBs is not possible, since otherwise, the composite EMF levels from the new gNB and the already-deployed base stations would surpass the (strict) limits. On the other hand, the presence of these zones may also alarm the population living in their neighborhood, and thus increasing the perceived health risks associated to the installation of new 5G gNB.

In the literature, different works [15], [72], [172], [192] focus on the analysis of saturation zones in cellular networks subject to strict regulations. In this context, the EMF levels are either estimated [15], [172] or measured in proximity to the installations [72], [192]. Focusing on the former category, the authors of [15] take into account the real base station deployment in an urban area in Naples (Italy). Results show that large saturation zones, in which the estimated EMF exposure is close to the limits, already emerge. The problem is also studied in [172], which is focused on the city of Bologna (Italy). By applying a set of conservative assumptions, which include, e.g., free space path loss and maximum radiated power from each deployed base station, the authors demonstrate the presence of high saturation levels for almost all the sites in the city center. Clearly, these sites can not be used to host any new 5G gNB.

In the following, we focus on the works tailored to the evaluation of saturation zones through measurements [72], [192]. Interestingly, the average exposure observed by [72], [192] is in general lower than the limits imposed by law. This outcome is expected, as the works based on EMF estimations [15], [172] typically introduce different assumptions, in terms of, e.g., path loss models or maximum output power, which may be very conservative in a real environment. Eventually, the authors of [192] performed in an situ-measurement campaign that was conducted in the same city of [172], showing that only less than 1% of the total base stations locations are actually saturated. In addition, the authors of [72] corroborate the finding of [192], by extending the analysis over a whole region, and by taking into consideration the measurement logs which were collected over almost 20 years. Interestingly, the average EMF levels present an increasing trend over the years, due to the installation of subsequent technologies and operators in the territory under consideration. In particular, if the EMF levels will continue to grow with the current trend, a complete saturation will occur in the forthcoming years. Hence, there will be no possibility to install any further cellular equipment co-located or in the vicinity of the already deployed base



Fig. 15. House close to a radio broadcasting tower in San Jose - CA (photo by Richard A. Tell). The EMF field measured in the proximity of the house was higher than 61.4 [V/m].

stations.

Summarizing, saturation zones are a consequence of strict regulations on EMF limits. In such zones, the installation of 5G gNBs would be very limited or even prevented at all. Despite this fact may be (wrongly) perceived by the population as an advantage in terms of health risks, it is solely due to the application of the strict regulations, which are not based on any scientific evidence for both short term and long term health effects.

2) Impact of Radio and TV Broadcasting

In the following, we move our attention to the coexistence of 5G with non-cellular technologies, and in particular, on radio and/or TV broadcasting. In this context, the authors of [174] performed a wide-scale measurement study to assess the EMF levels from radio and TV broadcasting in the USA, showing that the exposure was higher than 1 [μ W/cm²] for more than 440000 residents. The study was then updated 40 years later, showing that radio broadcasting radiates a consistently higher amount of power compared to cellular equipment [175]. The exposure from radio and TV repeaters w.r.t. cellular base stations is also analyzed by [72]. Results prove that people living in proximity to repeaters used for radio and/or TV broadcasting are subject to exposure levels higher than those living in proximity to base stations.

Summarizing, the exposure levels in the vicinity of radio/TV broadcasting towers are far to be negligible. Therefore, these sources should be carefully taken into account when deploying 5G gNBs, in order to minimize the health risks over the population. However, we need to remind that the emissions from radio/TV broadcasting are often under rated by the general public, which is apparently more concerned with the exposure from cellular networks. For example, Fig. 15 shows a photo of a house almost co-located with a radio tower. The EMF levels measured in the proximity of the house are higher

than the maximum limit imposed by law (set to 61.4 [V/m]).

3) Interaction of 5G with Weather Satellites

The 5G frequencies belonging to the 24.25-27.5 [GHz] and 37-40.5 [GHz] bands are close to the ones used by satellites for weather observation, i.e., 23.6-24 [GHz] and 36-37 [GHz]. Therefore, the power radiated by 5G gNB and UE may interfere with the sensing of water vapor and oxygen levels collected by the weather satellites, thus (possibly) impacting the weather information that is collected to monitor severe climate events, and consequently posing a health risk for the population [176]. Not surprisingly, this aspect is frequently reported by the opponents of 5G to increase the negative perception of such technology. More scientifically, the problem has been extensively studied by NASA and NOAA in [177], [178], which performed simulations with parameters set in accordance with ITU-R M.2101 recommendation [193]. Results show that a substantial noise limitation has to be imposed to 5G gNBs and 5G UE, in order to avoid interference problems with weather satellites. The outcomes of [177], [178] were also discussed during the ITU World Radiocommunication Conference 2019 [194], which instead defined limits on unwanted emissions for the total radiated power that are less conservative than [177], [178].

Several considerations hold when analyzing these outcomes from the perspective of communications engineering. First, the works [177], [178] assumed a pervasive deployment of 5G gNB and 5G UE operating at mm-Waves in urban zones. However, current indications point out that the adoption of 5G gNB will be rather limited, i.e., not deployed in whole urban areas like in [177], [178], but rather on specific locations (i.e., airport, stadiums, shopping malls). Moreover, the communications on mm-Waves will be one option among a set of possibilities, which will also encompass lower frequencies that do not interfere with the weather satellites. Fourth, as pointed out by [195], the input parameters used in the simulations of [177], [178] are based on very conservative assumptions, i.e., no beamforming capabilities, simultaneous transmission of gNB and UE in the same time slot, power overestimation for UE and gNB, lack of the 250 [MHz] guard band for 5G, and over simplified propagation conditions (without buildings and foliage). Therefore, the outcomes of [177], [178] may be not consistent with the ones achieved in a realistic setting. Third, the set of limits defined by [194] is incremental. More in-depth, looser limits will be initially applied to allow the installation of devices operating on mm-Waves. Then, after 1st September 2027, a new set of limits, more conservative than the current ones, will be applied. This choice appears to be meaningful, as the impact of interference may increase with the number of deployed devices. Fourth, as suggested by [194], solutions to avoid the antenna pointing in the direction of weather satellite sensors may be put into place in case interference problems are detected.

V. RISK MITIGATION TECHNIQUES FOR 5G EXPOSURE

We then move our attention to the possible techniques that can be put into place to reduce the health risks from the EMF exposure from cellular networks. We refer the reader to [196],

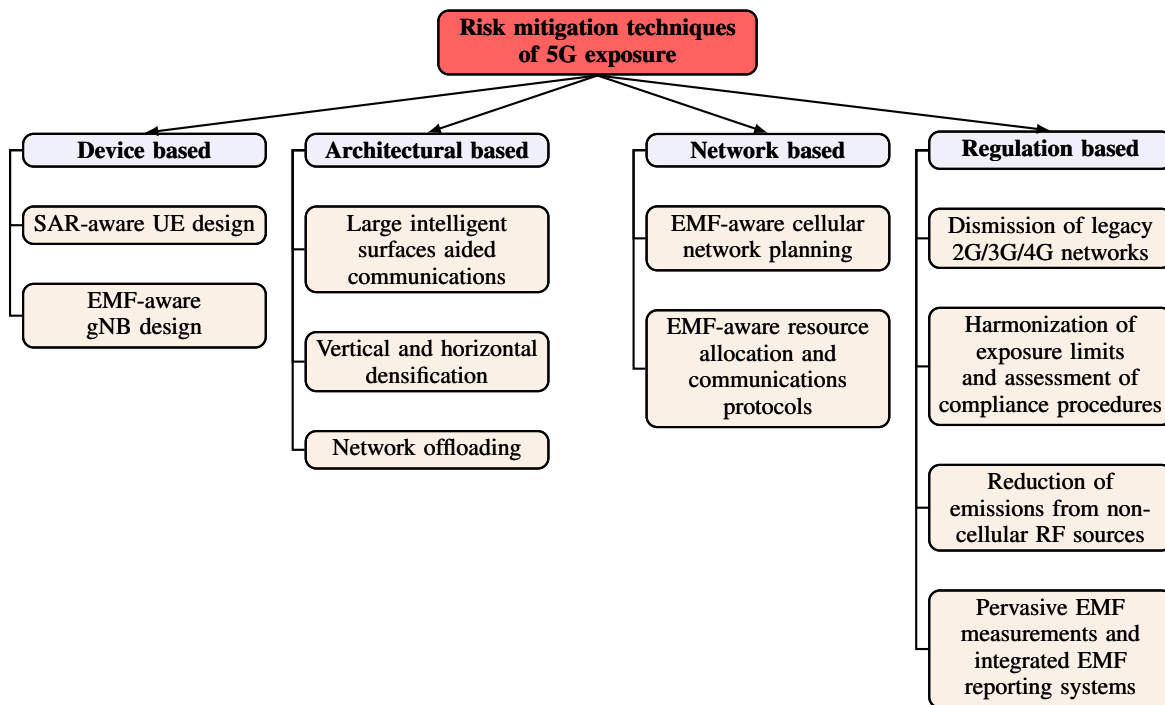


Fig. 16. Main techniques from the perspective of 5G communications to tackle the risk mitigation of 5G exposure.

[197] for an overview of the risk mitigation techniques in cellular networks. In contrast to [196], [197], this section is explicitly focused on the risk mitigation techniques tailored to 5G and beyond 5G networks.

Fig. 16 reports a graphical overview of the taxonomy that we employ to analyze the risk mitigation, which is observed through the lens of communications engineering. More in detail, we group the techniques into the following categories:

- 1) device-based solutions aimed at designing SAR-aware 5G UE or EMF-aware gNB;
- 2) architectural-based approaches aimed at reducing the risks by introducing new architectural features in 5G and beyond 5G networks, i.e., large intelligent surfaces aided communications, vertical/horizontal densification and network offloading;
- 3) network-based solutions aimed at developing EMF-aware planning solutions for cellular networks or at managing the radio resources and communication protocols to reduce the EMF;
- 4) regulation-based approaches are targeting risk reduction through the dismissal of legacy 2G/3G/4G networks, harmonization of exposure limits, compliance assessment procedures across the countries, definition of constraints to limit the emissions from non-cellular RF sources, and pervasively supporting EMF measurement campaigns and the EMF data integration across national and international databases.

A. Device-based Approaches

We initially focus on solutions targeting the reduction of exposure at the level of individual devices. Henceforth, we detail the design of SAR-aware UE and EMF-aware gNB.

1) SAR-aware UE Design

Traditionally, the goal of SAR-aware UE design has been pursued since the advent of cellular communications [198]. More in depth, previous techniques were focused on the reduction of the head exposure due to voice communications [199], [200]. To this aim, several techniques have been developed in the literature to shield the SAR generated towards the UE during voice calls [201]–[203]). The main shielding methodologies can be classified into: *i*) ferrite shields [201], *ii*) metamaterials [202] and *iii*) parasitic radiators [203]. In the following, we shed light on each of the aforementioned solutions. The review of other shielding methods (such as multi-antenna SAR codes, planar inverted-F antenna design, and angled helix antenna) are intentionally omitted here and left for future work.

In approaches based on ferrite shields, a ferrite sheet is introduced between the UE antenna and the external UE cover, in order to reduce the exposure to the head. Although the target of lowering EMF exposure is, in general, accomplished, the presence of the ferrite sheet may introduce negative impacts on the antenna properties. For example, according to [201], the antenna gain tends to be consistently reduced. In the context of 5G, this aspect may be a significant drawback, due to the fact that the antenna features have to be preserved, especially for mm-Wave frequencies.

A second approach to provide RF shielding is based on the exploitation of metamaterials, which are able to absorb the EMF from the UE antenna and consequently to protect the head [202]. Metamaterials are artificially fabricated materials with customized electromagnetic characteristics that do not exist in nature, e.g., a negative permittivity or permeability. The metamaterial shield acts as a band-stop filter that can be

tuned to the operating frequency of the antenna by adjusting the metamaterial dimension. Interestingly, simulation results indicate a 30% reduction in the SAR at the expense of a loss of almost 5% in the radiated power [202]. Eventually, the performance of ferrite sheets and metamaterials are compared using numerical simulation in [204], showing that ferrite sheets are in general more effective than metamaterials in reducing the SAR in the human head. However, it is important to remark that both [202], [204] are not tailored to 5G communications, which require the deployment of multiple antenna elements on the UE, and for which finding spare space for metamaterials may be a concrete issue.

Regarding parasitic radiators based approaches, the main idea is to employ a parasitic element that is embedded on the UE ground plane [203]. More in detail, the parasitic radiator is a passive element that is designed to control the current distributions on the ground plane, thus leading to a decreased SAR and an enhanced radiation pattern. However, the passive element tends to occupy space on the ground plane, which is already crowded with other integrated circuits required for the UE operation. This aspect may be an issue when considering 5G UE, which have to include a large set of circuits, and, in particular, the ones realizing wireless interfaces for 2G/3G/4G/5G and IEEE 802.11 connectivity.

In the following, we concentrate on other design choices that may be relevant to the reduction of SAR in 5G UE. The adopted techniques include: *i*) adjustment of UE radiation patterns to reduce the exposure [198] and *ii*) integration of multiple antenna arrays with dual-mode operation [205]. Focusing on the former solution, the authors of [198] define an antenna array design for 5G UE to reduce the body exposure associated with various mobile use cases, e.g., voice-calling, video-calling, and texting. In the analyzed scenarios, a set of smartphone sensors are exploited to infer the UE position and orientation. Then, the relative phase between the antenna elements is designed to direct the exposure away from the part of the body currently exposed to the specific UE usage. This technique is of particular interest to 5G, since the UE will be used for a set of variegated services, which will result in different exposure zones of the body, as well as different EMF levels, in contrast to previous studies focused only on head exposure [201]–[203].

A further improvement towards exposure reduction is then tackled by [205], which targets the SAR-aware design of beam-steerable array antenna operating at mm-Waves with dual-mode operation. The main idea is to employ two distinct sub-arrays that are placed in different UE positions, and consequently, generate different exposure patterns. More in detail, the first subarray is placed on the back cover, and it is activated only when the user exploits voice services. On the other hand, the second subarray is located at the upper frame, and it is enabled only when the user utilizes video or text services. By alternatively activating the two arrays (based on the type of services employed by the user), a peak SAR of 0.88 [W/kg] is achieved, a value much lower compared to other competing solutions [206], [207] that do not employ separate sub-arrays. However, the wide adoption of the proposed approach in commercial devices is still an

open issue, again under the light of the lack of space due to the presence of multiple wireless interfaces deployed on the same UE.

In summary, different techniques can be exploited to reduce the exposure from 5G UEs. Differently from approaches adopted for legacy technologies based on voice services, 5G-based solutions have to integrate a variegated set of exposure UE types. Also, the co-location of 5G antenna arrays with other wireless interfaces is already an issue, due to the limited available space on the smartphone. Therefore, future work is still needed to tackle the reduction of SAR for 5G UE at the device level.

2) EMF-aware gNB Design

The second approach to reduce the EMF is to target the design of gNB integrating exposure minimization. In contrast to legacy technologies, the massive adoption of MIMO and beamforming in 5G allows to dynamically focus the exposure on territory zones where the 5G service is currently needed. Thus, avoiding to pollute the other zones where the 5G services are not required. Therefore, an EMF-aware objective should be naturally targeted during the design of 5G gNB implementing MIMO and beamforming. Therefore, further research in the field should be devoted, e.g., for designing antenna elements that minimize the exposure outside the main focus of each beam. This last aspect, which is already tackled by 5G gNBs, is also linked to interference reduction and, consequently, increased throughput.

A second aspect, often underrated by the population, is that the design of base stations with EMF minimization is already in line with the goals of gNB manufacturers. In legacy technologies (pre-5G), in fact, a large fraction of the total base station power is used to feed its power amplifiers [208], [209]. In line with this trend, the definition of EMF-aware approaches for 5G gNB could lead to a reduction of the radiated power and, consequently, the associated electricity costs. In the literature, different works (see e.g., [210], [211]) are tailored to the energy-efficient design of base stations. However, the assessment of the proposed approaches in terms of EMF is, in general, not faced, while we advocate the need to integrate it in the context of risk minimization.

Eventually, we point out that different gNB types (e.g., small cells, macro cells) are subject to different levels of radiated power, and consequently of EMF exposure. For example, the ITU guidelines [212] define multiple power classes for the base stations. In the context of 5G, we advocate the need of pursuing different types of EMF-aware design approaches, tailored to the gNB classes. For example, the classes of gNB placed in close proximity to users (e.g., small cells and picocells) should implement the most sophisticated techniques to reduce EMF exposure. On the other hand, this goal is less stringent for macro gNBs, as the (not negligible) distance between the gNB and each user already contributes to limit the exposure.

B. Architectural-based Approaches

In the following, we focus on solutions that require a change at the architectural level (even going beyond currently

available 5G functionalities). To this aim, we analyze: *i*) communications aided by large intelligent surfaces, *ii*) network densification extended at both vertical and horizontal levels, *iii*) network offloading.

1) Large Intelligent Surfaces Aided Communications

The channel condition between gNBs and UE has a notable impact on human exposure to EMF. The unfavorable channel status is a crucial challenging issue for mm-Wave communications, where the LOS path can be easily obstructed by large-size and small-size blockages, e.g., buildings and humans. Traditionally, this problem is solved through the introduction of relay stations (see, e.g., [213]). By exploiting relays, in fact, the original long and obstructed path is split into a subset of links, each of them composed by a pair of interfaces in LOS conditions. When a single relay is exploited, the UE-gNB path is divided into two separate links, i.e., one between the UE and the relay, and another one between the relay and the gNB. From a communications perspective, relays can increase both the coverage and the network throughput [214]. Nevertheless, relays are active transmitters with full RF chains and dedicated power sources [215]. Therefore, from the health risk perspective, the systematic adoption of relay stations may further increase the EMF exposure over the territory.

In this context, a key question is: Is it possible to exploit the functionalities of relays, without introducing additional RF sources? One of the most promising techniques to tackle this question is the adoption of large intelligent surfaces aided communications. According to [216], such devices operate as smart passive controllable scatterers, and they can improve the wireless channel by reflecting the waves into desirable directions to create LOS link for the UE. More in detail, the reconfigurable intelligence surfaces can be fabricated from metamaterials that are equipped with programmable electronic circuits to steer the incident wave into customizable ways [217]. Compared to active relays, the scatterers are passive elements, and therefore they do not increase the number of RF sources radiating over the territory.

From a communications perspective, the adoption of large intelligent surfaces introduces notable advantages, which include: *i*) coverage probability and signal-to-interference plus noise ratio (SINR) improvement [218]–[220], *ii*) high energy efficiency [221] and *iii*) low transmission power (also in the uplink direction) [222]. The impact in terms of EMF has not been yet fully analyzed. However, we expect that the exploitation of large intelligent surfaces will be of great help in reducing the exposure (from both gNB and UE), and consequently, the associated health risks for beyond 5G networks [223]–[225]. Recently, several initial works consider the use of Reconfigurable Intelligent Surfaces (RISs) to reduce the EMF exposure [226]–[228].

To support the previous discussion with a clear example, Fig. 17 sketches a simple scenario where MIMO, beamforming and large intelligent surfaces are exploited. More in detail, the integrated architecture allows us to easily reach the Quality of Service (QoS) requirements of the users over the territory (e.g., the moving car in the figure or the neighborhood on the top left part of the figure), by always guaranteeing LOS conditions. On the other hand, the exposure will be diverted from sensitive

places (e.g., the central building in the figure). It is important to remark that the current pre-5G network (box on the top left of the figure) introduces an EMF exposure that is spread over the territory (including on sensitive buildings). Eventually, the future cellular architecture will also exploit narrow-beam FSO for backhauling to further reduce the exposure w.r.t. micro-waves links that are adopted in the current networks [229]–[231].

2) Vertical and Horizontal Densification

The goal of cellular densification is to increase the number of gNB serving a given portion of the territory. With vertical densification, the number of gNB is increased by deploying different cellular layers over the area (e.g., macro cells and small cells). This feature is already exploited in pre-5G networks [232], e.g., to provide primary coverage with macro cells and hotspot capacity with small cells. With 5G, the vertical densification will be a pivotal aspect to control the level of exposure. Thanks to the wide exploitation of heterogeneous networks, the (low) emissions from gNB will be concentrated on the zones where they are really needed (e.g., to provide capacity in hot spots), and not over the whole territory. In addition, the deployment of multiple layers of gNB will be exploited to improve the coverage and service of users. This aspect will be beneficial, especially for devices operating at mm-Waves, which are subject to strong attenuation effects, and hence require in general LOS and proximity to the serving gNB. In any case, however, research works tailored to the investigation of the EMF levels due to the large adoption of vertical densification in 5G are needed, both from theoretical and practical sides.

In this regard, an EMF aware approach with vertical densification is proposed in [233], where several receive-only tethered unmanned aerial vehicles (UAVs) are deployed to minimize the EMF exposure by vertically densifying the network for assisting the UpLink (UL). Nevertheless, research works that analyze the effect of densification not only for mobile users but also for the public with exposure metrics that leverage both uplink and downlink exposures.

In line with this trend, the exploitation of horizontal densification is another key feature to target the EMF reduction at an architectural level. The main goal of this approach is to increase the number of gNBs over the territory [234], in order to reduce the coverage size of each cell and (possibly) the radiated power. Differently from the vertical densification, which considers different types of gNB, the horizontal densification is realized by increasing the number of gNBs of the same type (e.g., only small cells). As already shown in Sec.IV-B, the horizontal densification is not a threat for the exposure levels, but rather an enabler for a low and uniform EMF over the territory. Certainly, strict EMF regulations may be a great barrier towards the horizontal densification of 5G networks. For example, in countries imposing minimum distances between gNBs (of every type) and sensitive places, horizontal densification will be a challenge, especially in densely populated areas that include a multitude of sensitive places. Although some previous research works try to shed light on a preliminary evaluation of EMF levels from horizontal densification in 5G networks [164], [235], [236],

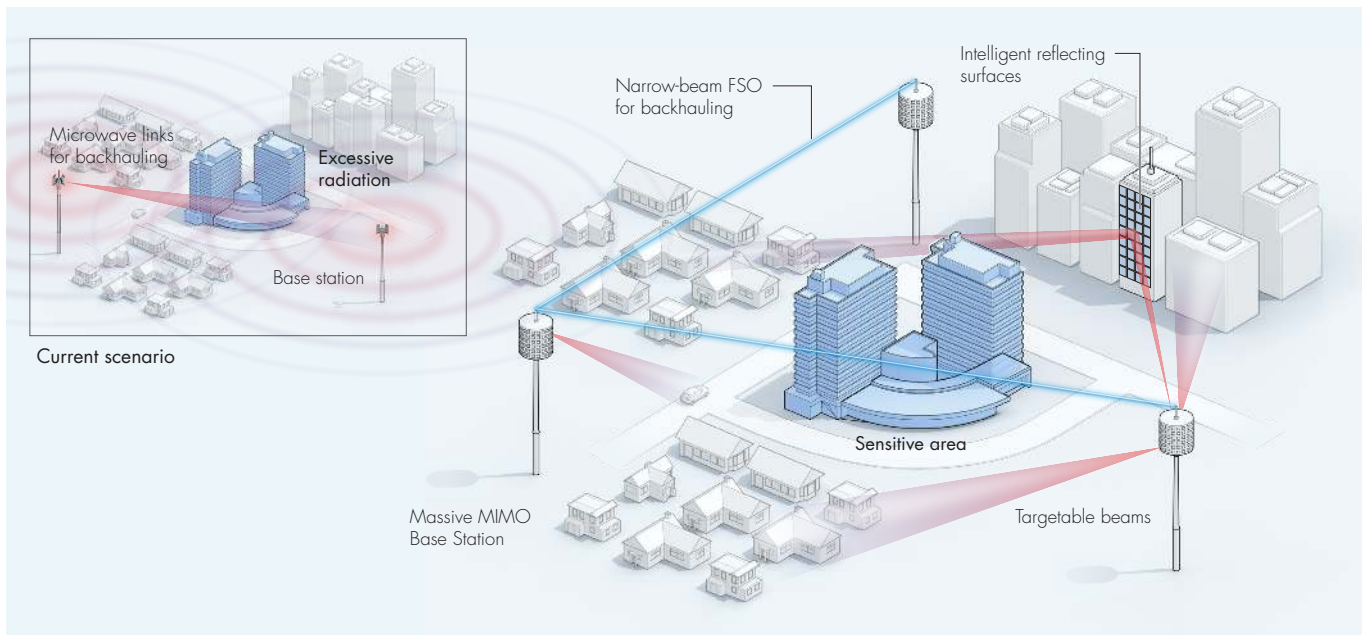


Fig. 17. An example of how the adoption of MIMO, beamforming, large intelligent surfaces and narrow-beam FSO can improve the service level and reduce the exposure levels over the territory (including sensitive places) w.r.t. current cellular networks.

future research is still needed, to properly take into account the specific 5G features and the impact from the national exposure regulations.

3) Network Offloading

The main idea of this approach is to move the user traffic from cellular macro cells to other wireless stations, e.g., Wi-Fi access points [237], small cells [238], light-fidelity (Li-Fi) attocells [239], and Terahertz access points [240]–[242]. In the following, we provide more details about Wi-Fi, small cell, and Li-Fi offloading techniques. Other types of offloading, e.g., from users to Mobile Edge Computing (MEC) servers [243], are intentionally not treated and left for future investigations.

Wi-Fi Offloading. Nowadays, Wireless Fidelity (Wi-Fi) is undergoing a paradigm shift toward ubiquity, with outdoor/city-wide wireless networks gaining continuous popularity. This trend is fueled by the release of the spectrum in 6 [GHz] band as an unlicensed spectrum [244]. In this scenario, the Wi-Fi 6E networks will make use of the additional spectrum, i.e., 1200 [MHz] in 6 [GHz] band, leading to higher data rates and lower latency [245]. To ensure such performance level, the Wi-Fi access points have to be deployed in proximity to users. In this scenario, the cellular operator can offload part of its own traffic to the Wi-Fi network. More in-depth, three different offloading strategies can be applied, namely: *i*) cellular network bypass [246], *ii*) managed offloading [247], and *iii*) integrated Wi-Fi core network [248]. With the cellular network bypass, the UE bypasses the mobile network by offloading the whole amount of traffic into the Wi-Fi network. With managed offloading, the operator manages a data session over the Wi-Fi lower layers. Hence, it has more control over the amount of offloaded traffic compared to the network bypass case. Finally, in the integrated Wi-Fi core network, the Wi-Fi access points are owned by the operator. Therefore, the traffic always traverses the mobile core network, and the offloading

procedure is completely transparent to the user.

From an exposure perspective, it is clear that the three aforementioned categories can greatly contribute in reducing the EMF levels, especially in the uplink direction. Although the number of works evaluating the benefits of Wi-Fi offloading in terms of exposure for pre-5G networks is overall limited (see, e.g., [249]), we believe that this architectural change could be of great interest in the context of 5G communications. Therefore, future works, tailored at the quantification of the exposure reduction due to Wi-Fi offloading in 5G networks, are needed.

Small Cell Offloading. The second approach to realize offloading is to move the user traffic from macro cells to small cells (including pico cells and femto cells). In this context, the offloading is beneficial to the EMF exposure perspective for several reasons. First of all, the transmitted power can be greatly reduced [15]. In addition, differently from Wi-Fi, small cells operate in licensed bands, and they are managed by the network operator. Hence, the problems of the reliability of the spectrum and integration issues are not so evident, as in Wi-Fi based offloading. Third, the deployment costs of small cells are consistently lower than those of macro cells, and hence, small cells can be beneficial candidates for a pervasive deployment in the context of 5G.

In the literature, different works [250]–[252] demonstrate that small cell offloading introduces several positive effects on the EMF levels from pre-5G networks. Thoroughly, a clear reduction in the uplink radiated power is achieved [250], [252], which can be coupled with a coordination of the inter-cell interference [251]. However, as shown by [253], the exposure in the downlink direction may be increased in proximity to the small cells. Therefore, we advocate the need to continue the research of exposure due to the small cell offloading in the context of 5G. Possible avenues of research include the

investigation of the impact of traffic-aware offloading strategies in dense 5G networks, where the amount of offloaded data depends on the specific 5G applications run on the user side. Also, the impact of handovers between small cells and macro cells on the exposure should be thoroughly investigated, e.g., by considering exposure-friendly small cell discovery protocols [254].

Li-Fi Attocell Offloading. A recent technique to perform offloading is to move the user traffic from macro or small cells to what is called Li-Fi attocells. Li-Fi is an entire networking system, similar in concept to WiFi, but it operates in the visible light frequency band, in contrast to Wi-Fi that uses RF [255]. Working at such a high-frequency band allows tremendous data rates due to the availability of large bandwidth. Nevertheless, as the frequency increases, the size of the cell decreases, leading to cells with tiny coverage area, i.e., attocells [239]. From the EMF perspective, offloading through attocells has more benefits compared to RF-based offloading techniques. The main reason is that Li-Fi technology relies on modulating the light that is already used for the illumination; hence, no additional RF waves are generated for data offloading, unlike offloading through WiFi and small cells. Nevertheless, the UE should be equipped with an additional transceiver consisting of light emitting diodes (LEDs) and avalanche photodetectors [256].

C. Network-based Approaches

The goal of network-based approaches is to tackle the risk minimization of human exposure by devising solutions in which the different 5G devices are jointly considered at a network level in order to reduce the EMF exposure over the territory. We divide the related literature into the following categories: *i*) EMF-aware 5G cellular network planning, and *ii*) EMF-aware resource management and communications protocols.

1) EMF-aware Cellular Network Planning

The planning of a cellular network under EMF constraints aims at selecting the set of base stations that have to be installed over the territory while ensuring economic feasibility for the operator, EMF levels below the maximum limits, and coverage and service constraints. Not surprisingly, this problem has already been faced in the past years to design 2G/3G/4G networks (see, e.g., [257] for the 3G case). Nevertheless, the planning of 5G cellular networks is a novel and challenging step, as pointed out by [15], [122]. The main reasons are that when considering 5G communications, the set of new radio features are introduced in this technology (e.g., in terms of MIMO, beamforming, and mm-Waves), 5G planning is coupled with the pervasive deployment of legacy technologies, and stringent EMF regulations are adopted.

More technically, the planning phase of a 5G cellular network requires the following input parameters: *i*) set of candidate gNB locations which may host 5G equipment; *ii*) set of possible configurations for each candidate gNB in terms of e.g., equipment type, radio parameters (e.g., adopted carrier(s) and bandwidth) and power parameters (e.g., maximum radiated power, radiation pattern for each radiating antenna, duplexing ratio between uplink and downlink communications);

iii) terrain description in terms of elevation, 3D modeling of buildings (including sensitive places) and obstacles (e.g., trees, lamps, bus shelters), already deployed RF sources contributing to the EMF (e.g., other base stations and/or TV/radio repeaters and/or civil/military radars); *iv*) spatial-temporal positioning of the users, *v*) minimum service constraints of users (by considering also their trajectories over the territory), *vi*) set of EMF limits and procedures to verify the EMF limits currently enforced in the territory under consideration. Given the aforementioned parameters, the network planning aims to find the subset of gNBs that have to be installed over the territory by balancing between the minimization of monetary costs for operators, maximization of service to users, and minimization of EMF levels over the territory. Clearly, a set of constraint has to be ensured, and namely: *i*) coverage over the area by the installed gNB, *ii*) guaranteed service constraints for users, *iii*) estimated EMF levels lower than the maximum limits imposed by law.

To the best of our knowledge, the closest works targeting the 5G network planning are [235], [236], [258]. Specifically, the work of Oughton *et al.* [258] is tailored to the assessment of the 5G planning by designing a new simulator, that can produce as an output the set of 5G sites and their configurations (e.g., in terms of radiating elements), by taking account multiple features, including the spectrum portfolio and the costs of the assets. However, the work is not tailored to the specific radio features of 5G networks (e.g., MIMO, beamforming, densification) and their evaluation in terms of EMF. In addition, irregular coverage layouts are not considered.

A cellular planning problem is also targeted by Matalala *et al.* [235]. Specifically, the goal of the authors is to tackle the trade-off between downlink power consumption, exposure from base stations (BSs), and exposure from terminals coverage in a cellular network exploiting MIMO. The authors then introduce two distinct objective functions, i.e., by considering downlink and uplink exposure as two separate metrics or as a single one. The problems are then heuristically solved on three scenarios based on a suburban area in Belgium. Results show that the number of users in the scenario strongly affects the exposure from gNB. In addition, the increase in the number of antennas elements triggers a decrease in downlink exposure and an increase in the uplink one. Moreover, the selected 5G planning achieves the same performance in terms of user coverage w.r.t. a 4G planning, coupled with a strong reduction in downlink exposure.

Eventually, Matalala *et al.* [236] focus on the problem of selecting the subset of MIMO BSs that minimizes the total power consumption, while ensuring coverage and capacity constraints. The considered scenarios include MIMO 5G configurations, as well as a reference one based on Long Term Evolution (LTE) technology. In addition, the problem is heuristically solved on a custom simulator. Results reveal that the increase in the number of deployed MIMO antennas can reduce the total power consumption compared to a 4G reference network while dramatically increasing the capacity offered to users. Moreover, the MIMO effectiveness in crowded scenarios with limited mobility emerges.

Although we recognize the importance of [235], [236], we

believe that substantial work is still needed to fully investigate the problem of 5G planning in the context of exposure minimization. To this aim, future research may be tailored to: *i*) a precise modelling of the key 5G features in terms of EMF levels, *ii*) the investigation of the EMF levels by considering the deterministic positions of the users over the territory *and* the beam configuration of gNBs in order to serve the users, *iii*) the evaluation of the impact of strict EMF constraints (e.g., exposure limits stricter than ICNIRP ones and/or presence of sensitive areas) on the obtained planning, *iv*) the evaluation of the 5G planning by taking into account the influence of legacy technologies (e.g., 2G/3G/4G) on the combined exposure levels.

Finally, we recognize that the EMF-aware 5G cellular network planning is typically solved by network operators thanks to the exploitation of commercial solutions (see, e.g., [259]). However, we advocate the need to closely involving the research community (including academia) on this aspect. On one side, in fact, innovative models to estimate exposure from 5G features could be defined. On the other hand, results obtained by organizations without economic ties to the problem may be a winning solution to publicly for demonstrating the benefits introduced by an accurate 5G planning on the exposure levels.

2) EMF-aware Resource Allocation and Communications Protocols

In general, the level of EMF exposure is affected by the amount of radio resources assigned to the user, e.g., time, frequency, and power, along with the considered communication protocols in different layers, e.g., physical, data link, network, and transport layers. Hence, efficient radio resource allocation schemes and communication protocols that aim at minimizing the exposure while preserving a target QoS can be interesting and effective solutions for risk minimization (see, e.g., [260] for the SAR case). This problem is similar, albeit not identical, to the well-established research of green communications [261]. The main difference between EMF-aware and energy-efficient approaches is that the first ones mainly focus on the exposure metrics that are closely related to the transmitted power from BSs and UE. On the other hand, the second approaches aim at minimizing the energy efficiency (e.g., in terms of joule/bit), including not only the energy spent in communications but also the energy that is consumed within the hardware components of gNB and UE. Although we recognize the importance of green communications, we consider henceforth the main works that are explicitly tailored to the EMF-aware resource management and communications protocols [262]–[268].

In this regard, [262] details a user-scheduling approach to reduce the uplink exposure in TDMA systems. The proposed solution manages the scheduling of the user transmissions depending on their total transmitted power in the past frames, leading to a reduction in the user transmitted power and consequently limiting the uplink exposure. Focusing then on OFDM based systems, which are typically exploited in Fourth-generation cellular network (4G) and 5G, the authors of [263] propose two resource allocation schemes in order to minimize uplink exposure, while guaranteeing a pre-defined

throughput for each user. More in-depth, the first approach is an offline algorithm that makes use of the availability of long term channel state information (CSI), while the second one is an online scheme that adopts the current CSI estimation. Results demonstrate that the proposed approaches are able to consistently reduce the user transmitted power compared to traditional solutions that solely maximize the spectral and/or power efficiency. The authors' work is further extended in [269] to the multi-cell scheduling case, confirming the positive outcomes in terms of uplink exposure reduction.

Focusing then on the downlink exposure, the authors of [264] design an algorithm for the exposure-aware association of UE to gNBs. Interestingly, results show that the exposure in massive MIMO 5G networks is almost one order of magnitude lower than the corresponding one from LTE systems with the same network coverage. However, the number of deployed gNBs in the 5G network is almost double than the one required in the LTE networks. This increase is justified by the authors of [264] due to the decrease of the downlink transmitted power of each antenna element in 5G w.r.t. 4G.

An influential aspect of controlling the EMF in cellular networks, exploiting beamforming (like 5G), is the design of beams. To this aim, the authors of [270] propose an algorithm to compute the beamforming vector to reduce uplink exposure. More precisely, the proposed solution can increase the antenna gains of the beams in the direction of the BS, while decreasing the localized SAR on the head. Eventually, the authors in [271] take into account both SAR and transmit power in the beamformer optimization process, showing that this approach allows a substantial performance improvement over schemes that are derived from solely power constraints.

The EMF reduction methods discussed so far are employed in the physical layer. However, the EMF exposure can also be minimized by considering higher layers, e.g., media access control (MAC), link, and transport layers. In this regard, a cross-layer EMF reduction approach combining features from physical and link layers is proposed in [265]. More specifically, an EMF-aware hybrid Automatic Repeat Request (ARQ) protocol is designed to minimize the number of re-transmissions, and consequently, the transmitted power, along with the latency. This methodology could be applied to the Ultra Reliable Low Latency Communications (URLLC) use case of 5G with efficient power transmission. On the other hand, [266], [267] investigate cross-layer approaches based on link and transport layers to target the decrease of EMF exposure in LTE networks. The solution proposed in [266] prioritizes the radio link control frames according to their significance in terms of QoS for video transmission over LTE. This approach can limit the number of re-transmissions for the non-critical frames, reducing the transmission power and, consequently, the EMF exposure. Eventually, the authors of [267] show that the cooperation between transport and link layers allows reducing the number of re-transmissions of non-critical data in video transmissions, which in turn decreases the uplink exposure, without jeopardizing the perceived QoS.

Although the previous approaches are promising in terms of exposure reduction, future works, tailored to the specific layers that will be implemented in 5G (and consequently to



Fig. 18. Evolution over the years of the measurement equipment to perform wide-scale EMF (photos by Richard A. Tell). The reduction of equipment size is essential to allow extensive EMF measurements from 5G gNBs.

the standardized features in this technology), are needed.

D. Regulation-based Approaches

The goal of regulation-based approaches is to enforce a change in the current EMF regulations to ease the installation of 5G networks while ensuring exposure limitation. In general, these solutions are pursued by decision-makers (e.g., national governments and international organizations), with a significant impact on the exposure levels.

1) Dismission of Legacy 2G/3G/4G Technologies

The deployment of 5G networks is currently done in parallel to the already deployed pre-5G systems. In a scenario where multiple RF sources already radiate over the same territory, and also in the presence of strict EMF regulations, the installation of 5G gNB is a challenging step, due to the fact there is a small room to install new gNB while ensuring the strict EMF constraints. To this aim, a possible solution could be the dismission of legacy 2G/3G/4G networks in favor of the adoption of 5G equipment.

Although this approach could be a great driver for the full exploitation of 5G technologies, its actual applicability is not a trivial task. For example, even by assuming the sole dismission of 2G networks, all the services currently in use by this technology will have to shift to 5G. This would include, e.g., most home alarm systems currently communicating through 2G interfaces, as well as voice services, which are still exploiting 2G in many countries. Even by assuming a smooth replacement of UE and other terminals with 5G interfaces, the deployed 5G radio access infrastructure should guarantee at least the same level of coverage provided by the 2G network that is dismissed. Despite these constraints, we believe that the disposal of the legacy technologies should be calendared in the activity list of national governments. This step could include, e.g., an incremental and selective dismission of pre-5G networks, where the legacy radio technologies are maintained in parallel to the deployment of the 5G network, for an amount of time defined in the regulations. As a step toward this goal, an operator in Netherlands has recently dismissed its 3G network, where the majority of users utilizes 4G instead of 3G services [272].¹⁵

¹⁵We would like to note that dismissing 3G cellular systems, and replacing them with 5G for data services could be easier than dismissing 2G networks.

2) Harmonization of Exposure Limits and Assessment of Compliance Procedures

As discussed in Sec. III-B and in Sec. III-C, the fragmentation of exposure limits as well as of the methodologies to assess the exposure compliance w.r.t. the exposure limits are a great barrier towards a uniform deployment of 5G networks in the world. Even when considering countries adopting international guidelines, there are clear differences that emerge, e.g., on the maximum limit values, the adopted metrics, and the assessment of compliance methodologies. In this scenario, it is desirable that international organizations will continue to promote harmonization procedures, which should be implemented in the national regulations. For example, in countries adopting strict regulations, the application of international guidelines (and consequently less strict limits), would ease the installation of 5G equipment over the territory. However, we recognize that this choice introduces non-negligible consequences at the political levels, as the risk levels perceived by the population may be increased due to the change of the exposure limits.

3) Reduction of Emissions from non-Cellular RF Sources

The emissions from radio and TV stations represent the largest contributions to human exposure [174], [175], especially for people living in proximity of radio and/or TV towers [72]. In the context of 5G deployment, it would be advisable to take counter-measures and reduce exposure from such non-cellular RF sources. Although the population does not generally associate high health risks to radio and TV towers (due to the fact that these technologies are in use for many decades), the reduction of exposure from these sources would ease the installation of the 5G equipment over the territory. Clearly, the services running on the legacy radio / TV architectures should be shifted to other technologies (e.g., satellites) or be included in 5G. In any case, however, the complete replacement of radio/TV equipment with 5G one is a challenging step.

4) Deployment of Pervasive EMF Measurement Campaigns and Data Integration

The high exposure dynamicity introduced by the novel 5G features (e.g., MIMO and beamforming), coupled with the exploitation of relatively new frequencies in the mm-Wave band, require to setup novel methodologies for the measurement and analysis of 5G exposure from gNBs. In particular, the implementation of continuous and pervasive EMF measurements

from 5G gNBs is crucial to face the perceived health risks from the population. Although the EMF meters have been continuously decreased in size and usage complexity in the last decades (as shown in Fig. 18), professional EMF meters are not intended to be used by the general public, due to several reasons. On one side, in fact, such devices are subject to high purchase costs, which introduce significant economic barriers against the deployment of pervasive measurement campaigns exploiting a vast number of meters. On the other hand, advanced technical skills are required to perform valid measurements, e.g., to avoid measurement errors and EMF contributions from other RF sources apart from gNB in the measurement campaign. As a result, the measurement activity is often performed by the technicians of EMF protection agencies. Clearly, assuming that these agencies will ensure a pervasive EMF monitoring for every location of the territory covered by 5G service is not realistic. In this context, the selection of a meaningful set of sites to concentrate EMF measurements will be an engaging and challenging future goal. Again, we believe that this problem can be solved with the help of the communications engineering community. For example, novel techniques for wide spectrum monitoring can be achieved by using sub-Nyquist analog-to-digital converters (ADCs) exploiting the sparsity and spatio-temporal structures of the measurements, in the context of compressed sensing [273]–[280].

A second aspect, which is often underestimated by the population, is related to the great benefits that could be achieved from the integration of the EMF measurements on common platforms at national and international levels. Providing a uniform set of interfaces to store, visualize, and analyze the EMF measurements from 5G devices (and especially from 5G gNB) would ease the reduction of the health risks perceived by the population. In addition, the sharing of the measurements across different communities would improve the knowledge about 5G exposure by allowing, e.g., the discovery of common exposure patterns and the presence of outliers/anomalies. However, this step requires effective coordination between the EMF protection agencies at the national level, as well as the integration of the measured data between the different countries. Eventually, we point out that this goal is being undertaken in some countries (see, e.g., [83] for the Italian case).

VI. SUMMARY AND CONCLUSIONS

We have performed an in-depth analysis of the health risks associated with 5G exposure by adopting the perspective of 5G communications engineering. Initially, we have concentrated on the health effects, by analyzing the central allegations of diseases linked to 5G exposure and by investigating the false claims and hoaxes. Besides, we have applied key concepts of communications engineering to review recent animal-based studies, demonstrating that the claimed health effects about the carcinogenicity of RF radiation can not be applied to 5G gNBs and 5G UE. Moreover, we have examined the population-based studies relevant to 5G, showing that their methodologies have to be deeply revised when considering 5G communications.

In the second part of our work, we have analyzed the basic metrics to characterize 5G exposure, in terms of incident EMF strength, PD, and SAR. We have then moved our attention to the PD/EMF/SAR limits that are defined by international organizations (IEEE, ICNIRP) and federal commissions (FCC), by also reporting a timely detailed comparison between the latest guidelines set in 2019-2020 against the previously adopted ones. To this aim, we recognize that the limits are pretty heterogeneous across the different authorities, although a harmonization effort appears for a subset of the considered metrics. In the following part, we have deeply analyzed the national regulations in more than 220 countries in the world, coupled with the actual deployment level of 5G technology. Overall, our picture reveals that there is a massive fragmentation of rules across the different countries (especially for gNB deployment), with many of these countries with unknown limits and no plans to deploy 5G, as well as a non-negligible amount of world population subject to strict exposure regulations. Clearly, for countries that adopt limits more stringent than ICNIRP/FCC ones, deploying the 5G networks and minimizing the perceived risks are two conflicting goals. Finally, we have analyzed in detail the different procedures defined by IEEE, IEC, and ITU to assess compliance of 5G exposure against the limits. Overall, we have found that the definition level of these approaches is already mature to be implemented in practice, although some guidelines have to be officially finalized.

In the third part of the paper, we have faced the main concerns associated with key 5G features, including: *i*) extensive adoption of MIMO and beamforming, *ii*) densification of 5G sites over the territory, *iii*) adoption of frequencies in the mm-Wave bands, *iv*) connection of millions of IoT devices and *v*) coexistence of 5G with legacy technologies. By applying sound concepts of communications engineering to review the related literature, we have shown that such features do not represent in general a threat to the population health.

Finally, the last part of our work has been devoted to the review of the main approaches that can be targeted to reduce the exposure from 5G gNBs and 5G UE, thus minimizing the perceived health risks. We have analyzed solutions working at the device, architectural, network, and regulation levels in-depth. Although some efforts have already been considered in the literature to reduce the 5G exposure, we have pointed out different avenues that could be followed in the future to achieve this goal fully. In particular, the role of the national governments in defining regulation-based solutions appears fundamental at this stage.

In conclusion, our work suggests that the health concerns about the deployment of 5G gNBs of 5G UE are not supported by communications engineering evidence. Therefore, there is no compelling motivation to stop the deployment of 5G networks, especially when precautionary principles are applied. However, we point out the importance of continuing to research possible health effects (not proven at the present time), associated with the realistic exposure (i.e., below maximum limits) of 5G devices. Clearly, we advocate further research works that aim to design exposure-aware cellular networks for 5G and beyond systems properly.

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