5G Public Private Partnership

Test, Measurement and KPIs Validation Working Group

EMF Task Force

Whitepaper

Beyond 5G/6G EMF Considerations

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Executive Summary

With the proliferation of advanced wireless communication technologies towards beyond the fifth generation (B5G) and sixth generation (6G), the available spectrum to be used is moving up in the gigahertz range and the density and directionality of emitting and receiving points, is certain to play an important role in achieving reliable and efficient communications. Due to the above and the emergence of new disruptive technologies, the electromagnetic field (EMF) exposure and related standards and measurements are destined to attract more attention.

Section 1 of this paper outlines the motivation and context of the 6G vison wherein EMF related aspects need to be considered, briefly illustrating the complexity and heterogeneity of the envisaged solutions.

In Section 2, we aim to provide a concise overview of the extensive, yet diverse, EMF limits standardisation around the globe, discussing to an extent the theoretical reasoning behind the standards, closing with a list of relevant and recent studies and papers on the topic.

Section 3 introduces the challenges, with regards to EMF in the B5G/6G era, highlighting some relevant use case scenaria.

The key metrics that can be addressed to measure the “performance” of a B5G/6G network environment with regards to EMF exposure are addressed in Section 4, along with some practical considerations on how to perform measurements.

Finally, we close with some remarks and suggestions for continuation of this work, in Section 5.

1 Introduction

This document provides an overview of EMF topics related to wireless communications and in particular to B5G and 6G systems. The relevant standards and effects are summarised, additionally, ideas on what and how to measure EMF effects are put forward as basis for further discussion and research. The available key performance indicators (KPIs) from the fifth generation Infrastructure Public Private Partnership (5G PPP) phase III projects with a focus on EMF are also consolidated with a view of how the KPIs are considered in the 5G system and how they may evolve in 6G systems.

1.1 Motivation

The discussion on EMF radiation of mobile networks has always progressed in parallel with the technological developments and has been especially accelerated since the introduction of millimetre wave (mmWave) technologies in 5G networks. This discussion is expected to further intensify with the development of 6G networks, due to the novel antenna technologies envisioned to be adopted and the increased availability of frequency spectrum.

The 5G PPP Test, Measurement and Validation (TMV) Working Group (WG) has published a white paper discussing B5G and 6G KPIs [1], which are well aligned with the KPIs described in the November 2022 version of the IMT-2030 Recommendations document [2], a vision document under development to cover networking, capability and usage scenaria for future communications.

Furthermore, [1] also proposes some additional KPIs which are relevant to and help better define the notions discussed in the IMT-2030 Recommendations document (e.g., computing resources, artificial intelligence (AI)). and it also brings forward topics such as EMF exposure.

In a similar fashion, the International Telecommunication Union Radiocommunciation Sector (ITU-R) Working Party (WP) 5D is considering the need for additional KPIs/ key value indicators (KVIs) within the IMT-2030 Vision Recommendation.

1.2 EMF TF within 5G PPP TMV WG

The TMV WG Group was founded as part of the 5G PPP effort to promote commonalities across projects that have strong interest in testing and monitoring (T&M) methodologies needed to provide support to the vertical use cases in 5G trial networks. Such efforts include the development of test and measurement methods, test cases, procedures as well as the KPI formalization and validation to the greatest possible extent, to ensure a unique European vision on how the entire lifecycle of the 5G network, ranging from research and development (R&D) to actual deployed environments, can be supported.

The group is comprised by several phase II and phase III 5G PPP projects, and deals with the following research areas and technology domains:

- Testing KPI definition, KPI sources, collection procedures and analysis
- Testing frameworks (requirements, environment, scenarios, expectations, limitation) and tools
- Testing methodologies and procedures
- KPI validation methodologies

- Testing lifecycle (i.e., testing execution, monitoring, evaluation, and reporting)
- Common information models for 5G T&M

Another important topic is the use of and contribution towards open-source projects such as open source management (OSM), open platform for network function virtualization (OPNFV) or open network automation platform (ONAP) and the identification of relevant exploitation and dissemination targets to promote the European vision on T&M towards a more global adoption.

In December 2022, it was discussed and decided to form a task force within the TMV WG, with the objective to provide a document with proposals on the EMF topics that the Smart Networks and Services Joint Undertaking (SNS JU) projects on 6G technology should address. The document was set to be finalized and become available by early July 2023.

1.3 B5G/6G Network Overview

Figure 1 depicts a high-level view of the 6G architecture and highlights the key technical enablers, as explained in detail in the 5G PPP Architecture WG white paper, "The 6G Architecture Landscape European Perspective", Version 6.0, February 2023. [3]

The various building blocks are organised into three layers: infrastructure, network service, and application layers. The infrastructure layer is comprised of radio access network (RAN), core network (CN), and transport networks, which contain radio equipment (non-virtualised radio functions like radio units (RUs), distributed units (DU), or even classical base stations), switches, routers, communication links, data centres, cloud infrastructure, and so on. The infrastructure layer provides the physical resources to host the network service (NS) and application layer elements.

Due to the introduction of new use cases, e.g., immersive smart city, the infrastructure layer envisioned for 6G contains RAN improvements that enable extremely low latency, high reliability, availability, high data rate, high capacity, affordable coverage, high energy efficiency, accurate localisation, and integrated sensing.

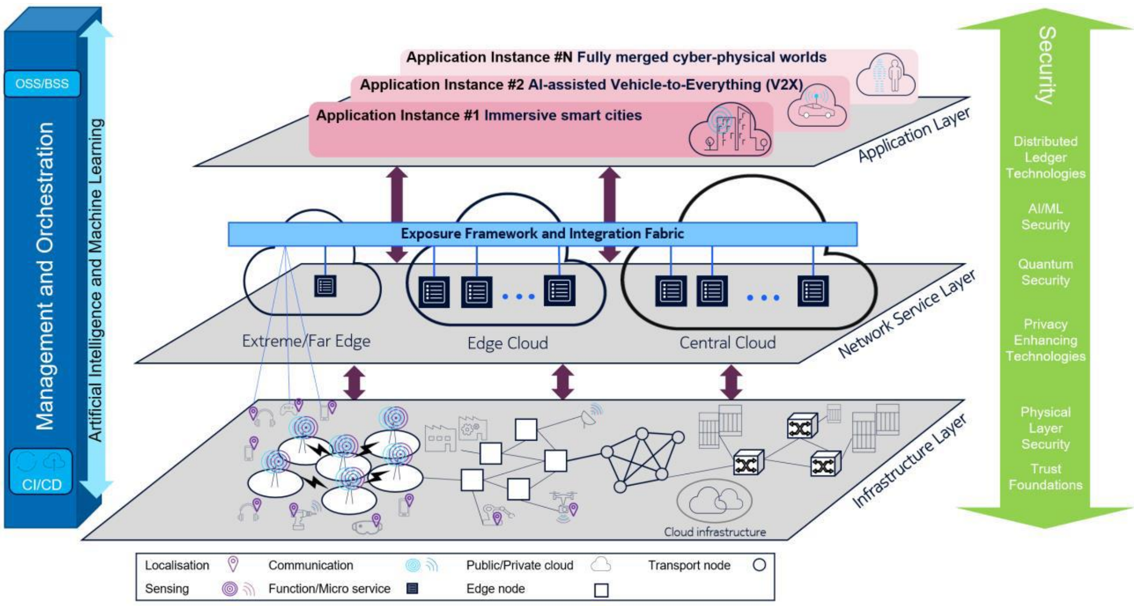

Figure 1. System view of the 6G architecture [3]

The 6G architecture incorporates different (sub)network solutions into a network of networks, as depicted in Figure 2. The network of networks can easily and flexibly adapt to new topologies to meet the requirements of both extreme performance and global service coverage, well beyond what 5G is capable of.

The infrastructure layer will probably comprise of the so-called heterogeneous network (HetNet) solutions, i.e., networks with both wide area macro and small cell pico base stations that should cooperate. The extension of the radio spectrum into mmWave in 5G added yet another aspect to flexible deployment. 6G deployments will include nodes using even higher sub-THz spectrum (e.g., in the 100-300 GHz frequency range) with limited coverage as well as nodes at low frequencies with seamless coverage, as illustrated in Figure 2Figure 5. Furthermore, the number of network solutions for capacity and coverage is also expected to increase in the 6G timeframe. These include solutions such as distributed multiple-input-multiple-output (D-MIMO) networks, non-terrestrial networks (NTN), campus networks, mesh networks, and cloudification of the network elements.

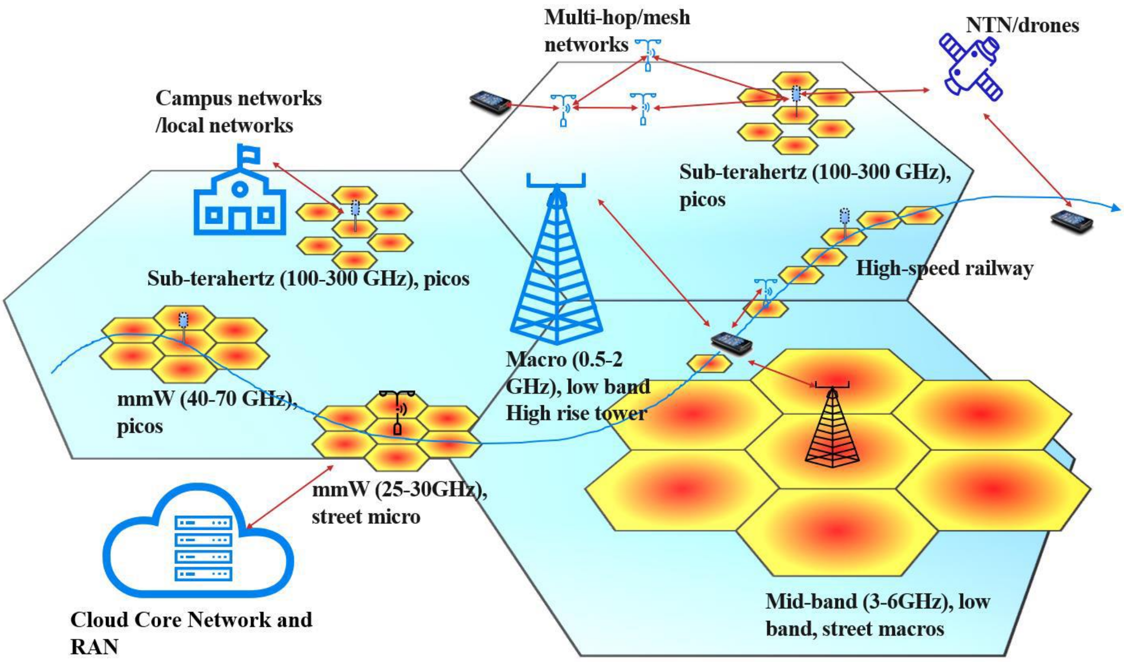

Figure 2. The 6G network of networks [3]

It follows from all the above, that the EMF effects of B5G/6G infrastructure networks will relate to a wide frequency spectrum in the GHz range.

2 EMF Effects, Standards and Studies Overview

This section presents an overview of the current state with regards to EMF effects, the associated standards and concludes with an overview of the recent studies and research activities on the topic, mainly coming from measurements and simulations with regards to the 5G era.

2.1 EMF Effects

Radiation limits are under discussion at regulatory/political level and in the general public. As shown in Section 2.2.2 the European Commission is following the radiation limits of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines (Section 2.2.1) from 1998 [4]. Due to further research and an update of these guidelines in 2020 [5], the European Commission initiated a study by the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER), whether the existing regulation needs to be updated [6]. The SCHEER came to the following conclusions:

- No moderate or strong evidence for adverse health effects from electromagnetic exposure at levels below the existing limits could be identified.
- However, there is a need of a technical revision of the annexes in the Council Recommendation on radiation limits (Section 2.2.2) to consider recently introduced dosimetric quantities and to establish limits for them.

The report is summarizing studies, whether there is evidence of increased risks by electromagnetic exposure on cancer, brain physiology and function, and fertility, reproduction, and childhood development. According to the report there was no evidence identified. However, in a small population of people non-specific symptoms were observed.

The report also investigated new technologies such as 5G, Internet of Things (IoT) and the impact at mmWave and Terahertz frequency ranges. Thermal effects, cellular interaction mechanisms, oxidative stress, genetic and epigenetic effects, calcium signalling and apoptosis were considered. According to the report there is no consistent evidence of biological effects that can support and strengthen the evidence on radio frequency (RF) exposure.

Health effects on neoplastic diseases, neurological and neurobehavioural effects, general symptoms, cardiovascular diseases, immune system, reproductive and developmental effects and auditory and thermoelastic effects were extensively studied in the report. There was no clear evidence. However, more research on potential effects other than thermal effects under specified and reproduceable conditions is recommended. More research at mmWave frequency ranges is needed.

Today, internationally accepted radiation limits in [4] and [5] are defined by thermal effects (threshold values) with a temperature raise of 1° C of the human body. Based on many studies this is regarded as the relevant health impact for very low intensity. Based on today’s knowledge from many studies there is no evidence of health effects with this definition.

2.2 Standards Overview

2.2.1 ICNIRP guidelines

The baseline document for the European Commission and national regulators for radiation limits for the exposure of electromagnetic fields are the ICNIRP guidelines in [4] and their update in [5]. These guidelines cover the frequency range from 100 kHz to 300 GHz, which is covering the frequency range, where the ITU-R Radio Regulation [7] has identified frequency bands to potential services. Most of the ongoing Terahertz research activities towards 6G systems are addressing the frequency range below 300 GHz.

ICNIRP is an independent scientific commission, which cooperates with organizations of the United Nations such as the World Health Organization (WHO), International Labour Organization (ILO), International Commission on Occupational Health (ICOH) and World Meteorological Organization (WMO), European Commission, and other international organizations like the International Radiation Protection Association (IRPA), International Electrotechnical Commission (IEC) and International Commission on Illumination (CIE). Commission members are experts in the field of non-ionizing radiation protection from all relevant scientific domains. Therefore, the ICNIRP guidelines are internationally recognized and accepted for radiation limits of electromagnetic fields. ICNIRP is the key international body for evaluating scientific studies and to set radiation limits as basis for regional and national regulations.

Radiation limits depend on the frequency range and use case. The ICNIRP guidelines provide reference levels for the following use cases [5]:

- for time averaged occupational exposures of ≥ 6 min: whole body and local exposures,
- for time averaged general public exposures of ≥ 6 min: whole body and local exposures,
- for exposure, averaged over 30 min and the whole body: occupational and general public,
- for local exposure, averaged over 6 min: occupational and general public and
- for local exposure, integrated over time intervals > 0 and < 6 min: occupational and general public.

Detailed diagrams and tables of the maximum allowed specific absorption rate (SAR) and specific energy absorption (SA) values, the electric and magnetic field strength for the frequency range < 2 GHz and the power density for the frequency range > 30 MHz are available in [5]. In the frequency range 30 MHz to 2 GHz the electric and magnetic fields strength and the power density are related for transversal electromagnetic (TEM)-waves by the field resistance Z_0 = 377 Ω. Figure 3 depicts an example for the general public.

SAR is a measure for the absorption of electromagnetic fields in materials, which results in a rise in temperature. It is measured as power per mass [W/kg].

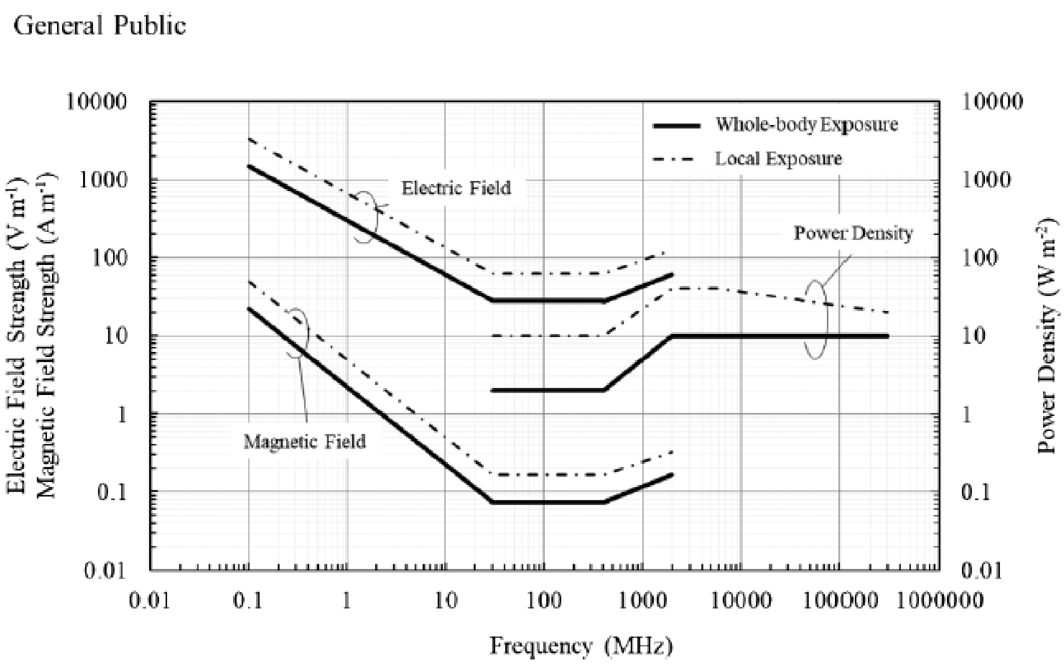

Figure 3. Reference levels for time averaged general public exposures of ≥ 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed root mean square (RMS) values; see Tables 5 and 6 for full specification) [5]

For example, in the frequency ranges for mobile and wireless communication the radiation limit for whole body exposure corresponds to 10 W/m^2.

2.2.2 European Commission Recommendations

The European Commission adopted in a council regulation [8] the ICNIRP Guidelines 1998 [4] as the basis for radiation limits in EU Member States. In the implementation of these limits additional security margins are considered, which may differ from country to country.

Figure 4 depicts the adoption of the ICNIRP guidelines (either 1998 or 2020) and EU Rec. 1999/519/EC across the EU/EFTA states, recreated based on data from [9].

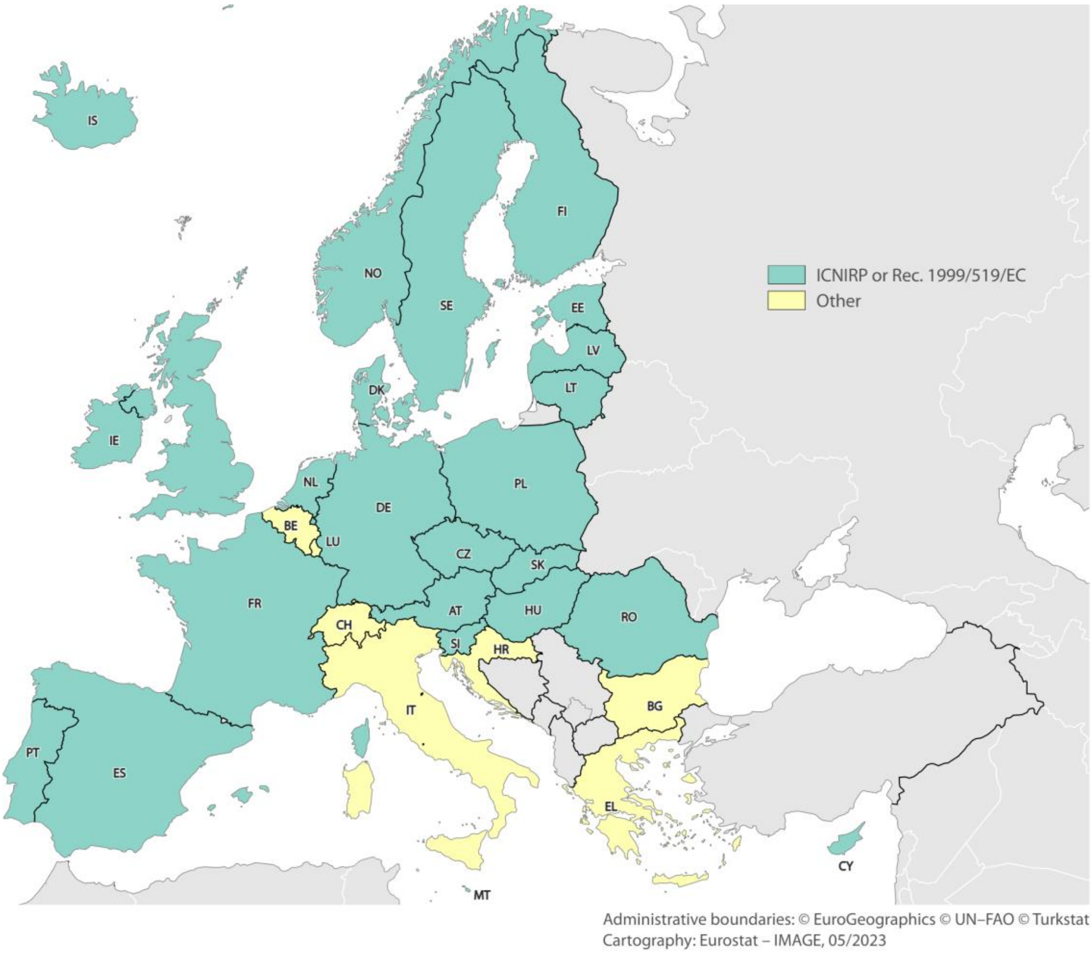

Figure 4. The state of EMF regulation adoption across members of the EU/EFTA states. Countries under "Other" group follow stricter restrictions compared to the limits set by ICNRIP or EU Rec. 1999/519/EC

2.2.3 ITU-T Electromagnetic field compliance assessments for 5G wireless networks

ITU, Telecommunications Sector (ITU-T) provides basic guidelines for the assessment of 5G and RF-EMF exposure [10]. These recommendations for 5G can be used as an example for the extension towards 6G and Terahertz systems. ITU-T is also referring to the ICNIRP guidelines in [4].

2.2.4 IEC standards

The IEC issued several standards and reports that are concerned with the evaluation of the human EMF exposure due to RF fields to ensure compliance with the national regulations or ICNIRP guidelines. IEC standards can be broadly divided into two categories; those concerned with the assessment of the RF field strength, power density and SAR near base stations, and those concerned with the evaluation of the RF field produced by mobile and handheld devices.

Under the first category is the IEC 62232 standard [11], which has been recently updated (October 2022) to account for the additional considerations that need to be taken for the newer technologies implemented in 5G and beyond such as mmWave and beamforming. It also considers for the assessment of the compliance of the base stations to the EMF limits the use of “actual maximum” transmission levels instead of the “absolute maximum” levels, which are unattainable in realistic operation conditions. Case studies of EMF exposure evaluations based on the IEC 62232 are presented in the IEC TR 62669, which consider early deployments of 5G scenarios [12].

The second category includes the IEC 62209 standards series [13], which provide the measurement and test procedures for the evaluation of the EMF exposure in terms of the SAR from wireless handsets and devices that are in use in close proximity to the human body and operating at frequencies from 4 MHz to 10 GHz. For frequencies above 6 GHz, the incident power density is the metric considered instead of the SAR. The IEC 63195 standards series [14] present best practices, measurement and computational techniques for the EMF exposure assessment in terms of the incident power density from handheld devices for the frequency range between 6 GHz and up to 300 GHz.

2.2.5 Implementation of radiation limits

The definition of the radiation limit with a maximum temperature increase of 1° C of the human body results in a threshold value of 4 W/kg for whole body exposure. In the implementation of radiation limits for mobile and wireless communication systems the two cases of base stations and mobile devices are distinguished.

In the case of base stations and for the general public a safety or reduction factor of 50 is applied, which is reducing the threshold value for whole body exposure to 0.08 W/kg. For occupational applications a safety or reduction factor of 10 is required with a threshold value of 0.4 W/kg.

In the case of mobile devices, local exposure to parts of the body needs to be considered, where higher threshold values apply according to [5]. For the general public, the threshold value corresponds here to 2 W/kg whereas for occupational applications it is 10 W/kg.

GSM Association (GSMA) published reports on the implementation of radiation limits for mobile communication networks in [15] and [16].

Some European countries require stricter safety or reduction factors, which is reducing the power density at humans. There is a trade-off between reducing the radiated power by increasing the safety or reduction factor further and an economically viable network deployment. A further reduced transmit power results in smaller radio range and requires the deployment of more base stations in the same area to ensure full area coverage.

2.2.6 Impact of radiation zones

In radio transmission, near- and far-field transmissions need to be distinguished. At the lower frequency ranges up to about 2 GHz, for mobile and wireless communication, the systems are operated in downlink under far-field conditions. On the other hand, at very high frequencies systems are often operated under near-field conditions. However, at high frequencies (mmWave, sub-Terahertz domain) and especially for antenna arrays, electrically big antennas with an aperture size $D_A > \lambda$ or $>> \lambda$ need to be considered, where near- and far-field regions r_1 and r_2 are increasing with frequency [17]. The human body is usually in the near-field of the mobile device antenna.

Massive MIMO (mMIMO) as applied in 5G and 6G systems requires bigger antenna arrays and is operated at higher frequency ranges with associated lower radio ranges. Therefore, base stations and mobile stations are often operated under near-field conditions, where far-field antenna patterns do not apply. Figure 5 shows the different radiation zones (Rayleigh distance r_1 – near-field region, Fresnel zone – transition region, Fraunhofer distance r_2 – far-field) and the relation between these distances and the ratio between antenna aperture size D_A and wavelength λ. With increasing frequency, near- and far-field regions are growing for $D_A > \lambda$

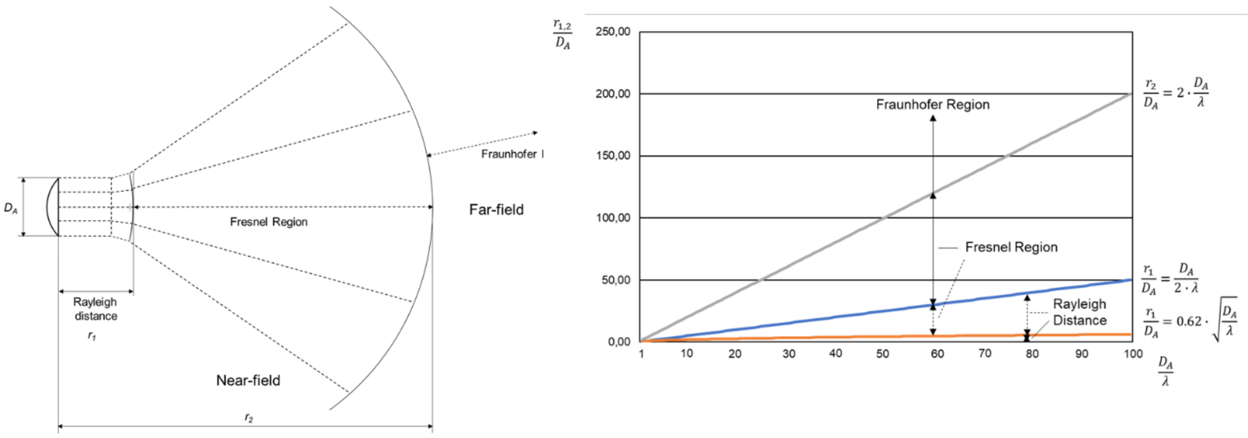

Figure 5. Near-field versus far-field [17]

Especially, for systems with very high frequency ranges the radiation limits cannot directly be applied, because systems are operated under near-field conditions. Here, more research is needed on how to apply radiation limits for base stations and mobile devices to meet the maximum raise in temperature of 1° C plus additional safety or reduction factors.

2.3 Overview of Current Studies

Most of current studies in the area of EMF exposure have been performed up to 7 GHz frequency range. This is called as frequency range 1 (FR1).

The French spectrum regulator ANFR has conducted a study [18] which compared EMF before and after the installation of 5G equipment and found that the radiation levels remained similar. The study was conducted between October 2020 and October 2021, nearly 1650 5G sites were measured, results were divided by frequency bands. 700 MHz and 2.1 GHz bands remained similar to measurements taken before 5G installations, 3.6 GHz band exposure increased slightly to 0.11 V/m. ANFR also did tests with simulating web traffic, EMF exposure did rise by about 16%.

Ofcom has been carrying out EMF measurements for many years. The results published have consistently shown that EMF levels are well within the general ICNIRP public EMF limits. The latest surveys could be found in [19]. 5G EMF exposure levels at 700 MHz and 3.4 GHz bands are shown as a percentage of the ICNIRP reference levels for general public exposure. The lastest reports state that EMF emission levels from 5G enabled wireless base stations remain well below the ICNIRP reference levels, with the highest level recorded being about 7.1% of the reference level (the next highest level recorded was 1.5%). The contribution of 5G to the total emissions levels is generally low; the highest contribution is about 0.04% of the reference level.

EMF exposure changes during a six-month period have been shown in [20]. In this study measurements have been collected for 5G and pre-5G EMF exposure from the considered location. The results show that 5G exposure is lower than pre-5G exposure, but it is visible that intensity and occurrence of 5G exposure peaks are increasing over the months.

Authors in [21] have shown that the maximum time-averaged power per 5G base station beam direction is well below the theoretical maximum and lower than what the existing statistical models have predicted. The results show that assuming constant transmission on peak power in a fixed beam direction could lead to unrealistically high EMF exposure levels.

In [22], the authors propose an RF EMF exposure assessment methodology for use with a common spectrum analyser. The proposed procedure has been validated on site for 5G NR operating at 3.5 GHz, while the authors claim that it should be applicable to any sub-GHz signal. For the use with mmWave, adjustments of the proposed measurement settings are needed as wider channel bandwidths with a larger sub-carrier spacing (SCS) are the norm. Only downlink EMF exposure is considered in this study.

The work in [23] reviews EMF radiation evaluation for 5G base stations on humans and this is written in the form of a review paper which also covers ICNIRP and the Federal Communications Commission (FCC) guidelines. Here both assessments based on a simulation model as well as an assessment based on field measurements on base station downlink EMF radiation are considered.

mMIMO will have effects on base station exposure as shown in [24]. The study executed a measurement campaign in order to measure EMF exposure from 5G NR base stations in a commercial network. The base stations operated at 3.6 GHz and used codebook-based beamforming. In combination of maximum downlink traffic and maximum extrapolated antenna input power, exposure levels reached 0.5-0.6% of the recommended reference level by ICNIRP.

The important question for 5G and B5G networks is how to plan radio networks when EMF constraints need to be applied. Authors in [25] have shown solutions for this question as well as demonstrated parameters which have an influence to reach an optimal solution. A large data throughput could be achieved with low average EMF exposure (less than 0.4 V/m) with optimal frequency reuse and taking into account pre-5G EMF exposure levels.

As most of the studies demonstrate, advanced features as beam forming are important functionalities to minimise EMF exposure. The narrower the beam the less EMF exposure is shown in study [26].

Ericsson has shown in their studies in [27] and [28] that the theoretical maximum power for all beams should not be assumed as this is not a very realistic scenario, also this assumption could cause unrealistically high EMF exposure level estimations in planning. EMF compliance assessments based on international standards IEC 62232 and ITU-T K.100 opened up to use actual maximum power as well. Based on these studies around 25% of the theoretical maximum power for 8x8 array antennas should be used as actual maximum power for 5G massive MIMO networks.

A recent paper [29] for EMF exposure in massive MIMO systems in 2,63 GHz and 3,65 GHz indicates through data and analysis, that EMF exposure due to 5G BS grows linearly with the number of utilized RF chains at the BS. Significant exposure variations can be also noticed according to the beam directions, i.e., the relative position of the exposure measurement location to the beam directions as well as the environment.

Studies on mmWave band, called frequency range 2 (FR2), are mostly around frequencies of 20 – 40 GHz.

EMF exposure assessment on 5G C-band and mmWave was performed in a study in 2022 [30] . The study considers the C-band at frequencies from 3.4 GHz to 4.2 GHz and mmWave, provides an overview of conducted studies and has tested EMF from base station with a fixed beam in order to validate the methods in a controlled environment.

The maximum RF-EMF exposure emitted by a 5G mmWave base station with MIMO antenna is measured in [31]. Six different tests have been performed with three different time frames, antenna directions and user equipment. Based on the results, the maximum and average exposure from 5G mmWave (30 GHz) are calculated. It was found that the maximum and average RF-EMF exposure of a single 5G mmWave base station is well within the limits set by the ICNIRP standard.

Human EMF exposure in 5G at 28 GHz is studied in [32]. This study proposes two case study models which they consider as “comparative”. The first model considers different wireless systems, i.e., 5G, 4G and 3.9G, and the second model compares between downlink and uplink. It is stated that the difference in cell size is a significant factor differentiating the level of EMF exposure among 5G, 4G and 3.9G. None of these three systems use any adaptive techniques as power control and adaptive beamforming. The study demonstrates how much EMF exposure is caused in a 5G system compared to 4G and 3.9G. The downlink and uplink case study illustrates geometric differences between the two directions of communication and considers beamforming on both directions. Here an adequate separation distance from transmitter has been suggested.

The downlink traffic is an important factor to consider when evaluating EMF exposure. A commercial 5G scenario in [33] has revealed that the exposure from the mmWave base station is proportional to the amount of traffic on the downlink. However, the EMF exposure has been shown to be always lower than 0.08 V/m even with a large downlink traffic (more than 800 Mbps).

3 EMF Challenges

3G, 4G and 5G networks produce radio-frequency electromagnetic fields which are used to transmit information. Electromagnetic fields have been around in different forms since the birth of the universe, and they differ from each other by frequency. In addition, radio-frequency electromagnetic fields were already produced prior the emerge of mobile networks e.g., from TV and radio broadcasting sites, radar, electrical grids etc.

From the introduction of mobile communication technologies, there has been some public concerns about the potential health risks associated with the use of mobile phones and living near base stations. Despite extensive studies on the health effects of mobile phones over the last two or three decades (focusing on 2G, 3G and 4G mobile networks), there is no indication of an increased health risk when exposed to electromagnetic fields below the levels specified by international bodies [34].

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

- A clear definition of the new studies that need to be conducted, fine-tuned to the new 5G/6G technologies and characteristics
- A well-defined set of EMF related KPIs
- A well-defined set of EMF measurement and monitoring methodologies

In addition, the radio frequency exposure guidelines and limits (described in detail in section 2.2) are under further consideration and monitoring from ICNIRP and other organizations. Of course, in our work, we adopt the current exposure guidelines and limits, and we will update only in response of any new guidelines from the above organizations.

3.1 Technology and Frequencies

During the short lifetime of the EMF TF, we had extensive discussions and we made initial considerations about the 5G/B5G/6G technologies that have an impact on the EMF values. The technologies identified are the following:

- Massive MIMO: mMIMO technology is one of the major keys to provide extremely fast data rates in 5G/B5G mobile networks, because a larger number of antennas enable higher spectral efficiency and better energy efficiency can be achieved. Regarding EMF considerations, the equipment of base stations with arrays of many antennas results in increasing the total RF EMF generated by the mobile sites.
- Beamforming techniques: beamforming is the application of multiple radiating elements transmitting the same signal at an identical wavelength and phase creating a narrower, more targeted stream. Beamforming techniques are drastically increasing the antenna gain and therefore – if directed to the user – can drastically increase the supported data rates. Regarding EMF considerations, although the total EMF values may be kept similar, this directionality of generated electromagnetic field highly increases the EMF values in the main lobe, while decreases the EMF values in the side lobes.
- Site densification: the further densification of mobile networks in 5G and B5G introduces more mobile sites as well as micro- and pico- mobile stations located very close to the general public. Therefore, new EMF studies should be conducted which take into consideration the new realities.
- Carrier aggregation: carrier aggregation allows mobile networks to combine multiple channels (or carriers) to deliver greater speed and performance and higher coverage. Regarding EMF considerations, the use of multiple carriers in different frequency bands increase the total EMF value for each mobile user.
- Transmission frequencies: the introduction of new technologies operated in lower or higher spectrum bands may affects the correlation of measured EMF exposure to the limits. E.g., transmission in low frequency bands in which the limits have lower values (e.g., 800 MHz).
- Waveforms: the new waveforms adopted in 5G / B5G / 6G mobile networks have shorter bursts and higher peaks. This fact should be taken into consideration, both in the EMF measurement methodology and during the analysis and evaluation of the results. Some questions which arise are: a) are the current methodologies capable of capturing very short bursts or do we need to update them? b) Do we need to make any extrapolation after the actual measurements in order to better capture these bursts?
- Co-existence of technologies: the co-existence of several technologies and mobile generations in a mobile site is imposed either by backward compatibility to previous

generations of mobiles or for supporting carrier aggregation. Regarding EMF considerations, the retainment of equipment for supporting several mobile generations in the same site, increase the number of antennas and the total EMF values of the site.
- Near- and far-field consideration: especially at higher frequency bands with high antenna gain and low radio range, uplink and downlink are usually operated under near-field conditions. Research is needed how to consider near-field conditions with respect to radiation limits.

3.2 Draft Scenaria/Use Cases

As already stated previously in this document, extensive studies into the health effects of mobile phones over the last two or three decades were conducted and no indication of an increased health risk was identified. Therefore, the new studies should not start from scratch, but rather complement the already conducted studies with new scenarios fine-tuned to:

- the new technologies introduced by the 5G/B5G/6G mobile networks
- the new frequencies supported by the 5G/B5G/6G mobile networks
- the new realities in the mobile environment (e.g., site location)

In addition, based on past experiences (older studies) that investigated and established that the measured EMF values are far from the limits, there is no meaning of selecting all the possible scenarios but rather focus on the worst-case scenarios.

These worst-case scenarios can be defined by:

- the positions around the mobile site with the higher theoretical expected EMF values
- the positions in selected technologies with the theoretical higher expected EMF values
- the selection of technologies transmitting in the frequency bands with the strictest (lower) limits
- the co-existence of several technologies and mobile generations on the same mobile site
- the collocation of several mobile providers on the same mobile site
- the combination of the above characteristics

Some indicative examples in line with the aforementioned proposals can be found below:

- A mobile site on the roof top of a fifth-floor building, residents on the sixth floor of a neighbouring building
- Sitting place of a restaurant/coffee shop in front of a small cell inside a shopping mall
- Co-existence of 3G, 4G and 5G technologies on the same mobile site
- Collocation of three mobile providers on the same mobile site

4 Relevant Key Performance Indicators

4.1 Basic Measurements and KPIs

The measurements pertaining to EMF exposure can intuitively lead to relevant KPIs that have then to be correlated to the reference levels of the associated standards.

For high frequency environments of interest (GHz region), the standards specify:

- **Specific absorption rate (SAR)**, in Watt per Kilogram (W/kg)

As basic value to be measured. SAR measurements are performed in the reactive near-field (e.g., body-worn devices). It can be measured in laboratory conditions with specific setups, artificial head and non-electric liquid. Several adaptation parameters are also needed to emulate free space resistance Z_0.

The derived quantities that are measured in the far-field and could therefore be considered as measurable KPIs, are:

- **Electric field signal strength**, in Volt/Meter (V/m)
- **Magnetic field signal strength**, in Ampere per Meter or Tesla (A/m)
- **Power flux density (PFD)**, in Watt per Square Meter (W/m^2)

4.2 Correlation of EMF Exposure Measurements to the Limits

For continuous-wave transmissions, including very high frequency (VHF) frequency modulation (FM) radio - since these signals remain fairly constant in amplitude - flat (broadband) probes can be used for measurements.

The conversion from signal strength in V/m to PFD in W/m^2 can be done using the formula below:

$$PFD = (V/m)^2/377\ \Omega\ (W/m^2)$$

(The intrinsic impedance of free space is 377 Ω).

e.g., 6 V/m (ICNIRP 1800 MHz) = (6*6) $(V/m)^2/377\ \Omega = 0.095\ W/m^2 \approx 10\ \mu W/cm^2$

The actual frequency, which the measurement probe cannot inherently determine, is irrelevant to the evaluation.

Therefore, an emitter with PDF of 10 $\mu W/cm^2$ is always at 100% of the radiation limit value, independent of the frequency.

However, once we turn our attention to the sub-GHz and GHz frequency range, the thermal effects of the EMF radiation and their variation with frequency become of significance, not only due to the energy increase but also the absorption resonance to different parts of the human body, as shown below in Figure 6.

For adults, the resonance range for maximum absorption is approximately between 30 and 100 MHz (see Figure 6) because the body dimensions and wavelength of the field are in the same order of magnitude (the so called antenna effect, which occurs when the body height matches half of the wavelength – e.g., at a body height of 1.80 m, it is an 83.3 MHz field with a wavelength of 3.60 m).

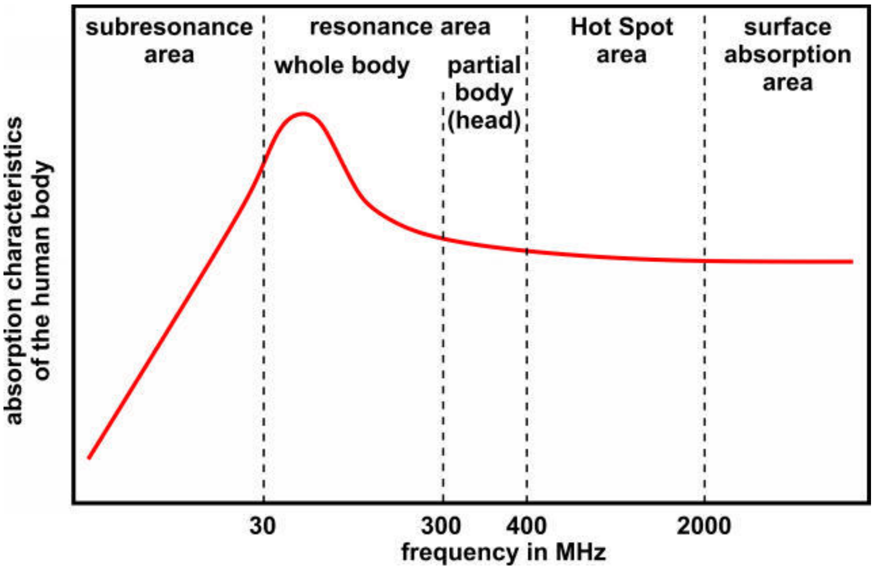

Figure 6. Absorption of radiofrequency fields in the human body depending on the frequency [35]

Then in order to be able to measure EMF exposure and correctly correlate the results to the limits, the measurement probes should be able to take into account the shaping effect with regards to frequency variation (as depicted schematically in Figure 7 below) and not only calculate the total values.

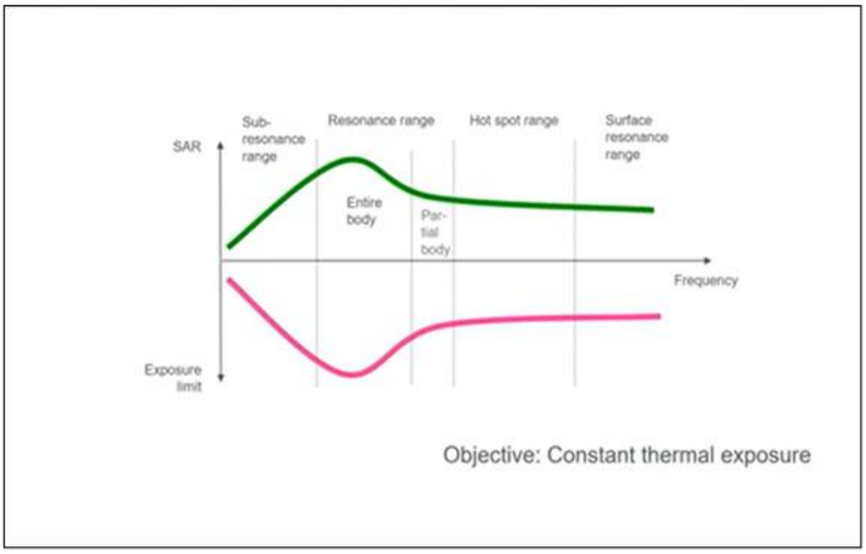

Figure 7. Resonance and Stipulation of Limits [36][35]

To illustrate this, let us look into the example of the following Figure 8 where the different spread of the same total PFD, 5 mW/cm^2 in the example, (denoted as S) at various frequencies (Table 1), can lead to dramatically different end results, with regards to the limit values.

In Case 1, we only reach 71% of the limit values, while in Case 2 the total exposure shoots to 169% of the limit values.

Table 1 - EMF Measurements for 2 different cases [36]

Frequency (MHz)	Limit (mW/cm^2)	S (mW/cm^2) (Case 1)	% of Limit (Case 1)	S (mW/cm^2) (Case 2)	% of Limit (Case 2)
1	**100**	4	4	2	2
100	**1**	0,5	50	1	100
900	**3**	0,5	17	2	67
		5	**71**	**5**	**169**

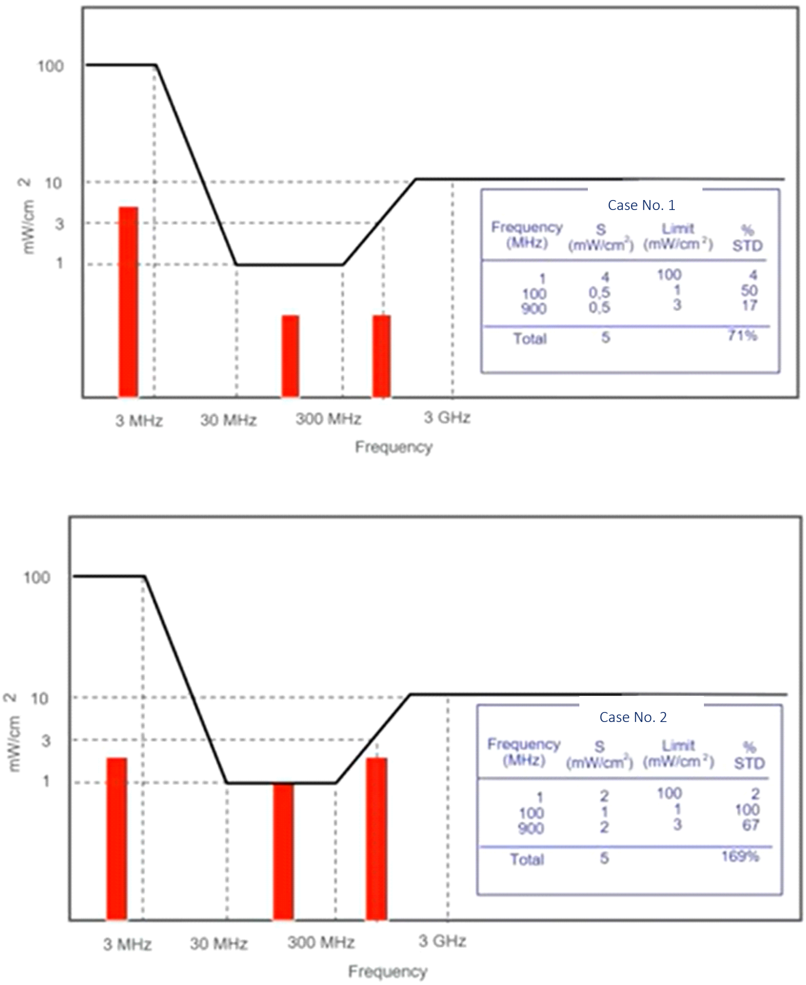

Figure 8. EMF Measurements shaping effect [36]

A specific approach to measuring EMF radiation is proposed by the ICT-52 project RISE 6G [1], [37], This adopts two composite EMF KPIs, suitable for the specific case of measuring EMF exposure from reconfigurable intelligent surfaces (RIS), as summarised in Table 2 below.

Table 2 - Composite EMF exposure KPIs suggested by RISE project [37]

KPI name (project)	**Self EMF exposure**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	For the uplink communication direction, S-EMFEU = R_UL/X_I, where R_UL is the data rate that is transmitted by the considered user in the uplink direction and X_I is the EMF to which the same considered user is exposed. Note that the considered user can be seen as an uplink "intended" user.
Standard definition	IEC 62209-1/2 [13] (Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Human models, instrumentation, and procedures)
Target value (project)	A first measurement of the metric will be performed in the absence of the reconfigurable intelligent surfaces RIS(s): M1. A second measurement will be performed in the presence of RIS(s): M2. We expect to observe a gain G=10*log10(M2/M1) of several dBs.
Other remarks	In connection with these measurements, the limits set by EU and national agencies should also be considered.
KPI name (project)	**Inter EMF exposure**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	For the downlink communication direction, I-MFEU is defined as I-EMFEU = R^DL/X^NI, where R^DL is the data rate that is delivered to the intended user and X^NI is the EMF to which the non-intended user is exposed. When considering multiple non-intended users, X^NI is the EMF of the most exposed one.
Standard definition	IEC 62232 [11] (Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure)
Target value (project)	A first measurement of the metric will be performed in the absence of the RIS(s): M1. A second measurement will be performed in the presence of RIS(s): M2. We expect to observe a gain G=10*log10(M2/M1) of several dBs.
Other remarks	In connection with these measurements, the limits set by EU and national agencies should also be considered.

4.3 How to Measure: Network vs. Safety Issues

An ideal assessment method for the exposure due to non-electrostimulation effects of external electromagnetic fields in an area of interest that could be formulated (according to ITU [38]), as follows:

- With mmWave transmissions being highly directional, a measurement of the squared, isotopic and weighted RMS value of the electric and/or the magnetic field strength at any position in the area of interest where humans are likely to be exposed should be considered.
- The use of only moderate or no spatial averaging around each position with care taken towards identifying and assessing potential multi-path interference.
- Make sure that the risk of human exposure is limited during measurements.
- Exclude any position from the measurements where the distance to conductive objects is less than 0.5 m.
- If extrapolation techniques are not considered, use an RMS integration over time, which is not longer than the maximum permissible integration time.
- Measure over a time span, which is long enough to ensure that the maximum exposure over time will occur within this chosen time span.
- Use the maximum exposure value of all positions and over the complete observation time as the final exposure result. If this result is less than unity, the exposure in the area of interest is permissible.

While this 'ideal' assessment method will prove challenging due to too many points in space and time and how a position in space and time is quantified, it clearly shows the objective of real assessment methods that should be considered for further investigation.

5 Conclusions and Next Steps

In the preceding sections we provided an overview of the EMF exposure related aspects that come into play in B5G/6G network environments. We discussed the relevant standards, effects, and basic techniques to measure EMF exposure. We introduced the particularities and challenges of identifying the most appropriate and practical EMF performance attributes.

With the advent of B5G and 6G communications and applications, EMF radiation KPIs need to be addressed so that most (worst) case scenarios are covered, based on the parameters identified, in previous sections.

It is this area in particular, where we feel that further investigations and research activities are warranted. To that effect, SNS JU could steer activities towards collection and evaluation of EMF KPIs in current and future projects.

Other KPIs such as energy efficiency, may also be an important topic in the sense that optimized transmission power will positively affect EMF exposure. Furthermore, EMF measurement methodologies, guidelines and future recommendations will need to reflect the possible effects of moving to higher frequencies (e.g., above 300GHz and THz).

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Abbreviations and Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
5G PPP	5G Public Private Partnership
6G	6th Generation
AI	Artificial Intelligence
ANFR	L'Agence Nationale des Fréquences (French national agency for frequencies)
B5G	Beyond 5G
CIE	International Commission on Illumination
CN	Core Network
D-MIMO	Distributed multiple-input and multiple-output
DU	Distributed Unit
EMF	Electromagnetic Field
EMFE	Electromagnetic-Field Exposure
EMFEU	EMFE Utility
EU/EFTA	European Union / European Free Trade Association
FCC	Federal Communications Commission
FM	Frequency Modulation
FR 1	Frequency Range 1
FR 2	Frequency Range 2
GSMA	Groupe Speciale Mobile Association
HetNet	Hetrogeneous Networks
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICOH	International Commission on Occupational Health
ICT-52	EC Information and Communication Technologies calls -52-2020
IEC	International Electrotechnical Commission
I-EMFEU	Inter-EMFEU
ILO	International Labour Organization
IMT	International Mobile Telecommunications
IOP	Institute of Physics
IoT	Internet of Things
IRPA	International Radiation Protection Association
ITU-R	International Telecomunication Union - Radiocommunication Sector

ITU-T	International Telecomunication Union - Telecommunication Standardization Sector
KPI	Key Performance Indicator
KVI	Key Value Indicator
MIMO	Multiple Input Multiple Output
mMIMO	Massive MIMO
mmWave	Milimeter Wave
NS	Network Service
NTN	Non-Terrestrial Networks
ONAP	Open Network Automation Platform
OPNFV	Open Platform for Virtual Network Functions
OSM	Open Source Management
PFD	Power Flux Density
RAN	Radio Access Network
R&D	Research and Development
RF	Radio Frequency
RIS	Reconfigurable Intelligen Surface
RISE-6G	Reconfigurable Intelligent Sustainable Environments for 6G Wireless Networks
RMS	Root Mean Square
RU	Radio Unit
SA	Specific Energy Absorption
SAR	Specific Absorption Rate
SCHEER	Scientific Committee on Health, Environmental and Emerging Risks
SCS	Subcarrier Spacing
S-EMFEU	self EMF Exposure Utility
SNS JU	Smart Networks and Services Joint Undertaking
T&M	Test and Measurement
TEM-waves	Transversal Electromagnetic Waves
TMV	Test, Measurement and KPI Validation, 5GPPP WG
VHF	Very high frequency
WHO	World Health Organization
WMO	World Meteorological Organization
WP	Working Party

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