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SURVEY

# A Survey on EMF-Aware Mobile Network Planning

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**ABSTRACT** Considering electromagnetic field (EMF) exposure from the radio frequency (RF) domain has always been critical in deploying new cellular network technologies. European countries implement strict limits to ensure that a radiating element such as a cellular antenna cannot exceed a certain threshold in the vicinity of urban or densely populated areas. Before 5G, these limits could easily be managed with calculation methods during the network planning phase, i.e., before the physical installation of antennas. These previous-generation transmitters act statically, and it is usually simple to respect EMF limit values while ensuring adequate quality performance for end-users. Current active antenna systems benefit from Massive MIMO (Multiple Input, Multiple Output) technologies with Time Division Duplex (TDD) and precise beamforming. These technologies employed by 5G enable antennas to behave dynamically in time and space, depending on the distribution of users and the applications targeted. This new dynamic behaviour, together with larger antenna arrays, makes the estimation of RF-EMF exposure more complex, usually leading to overestimations. The only solution to lower this exposure and to make an installation compliant is to lower the output power, which potentially limits the performance of current 5G networks. In the future, as new frequencies and multiple deployment points emerge, this exposure overestimation, associated to strict regulations, could drastically restrict or even prevent the deployment of communication technologies (5G Advanced, 6G). This survey provides an overview of this broad area, looking at the global and European regulatory frameworks and then taking the case of Luxembourg, which has lower limits than most EU countries. It then references the main EMF exposure estimation methods available in the literature applied for 4G and prior generations before focusing on potential and not yet standardised approaches for 5G. The perspective is then changed to discuss the issues related to network planning and the interest in using optimisation approaches. Finally, the survey concludes by summarising the gaps and opportunities related to EMF-aware network planning solutions.

**INDEX TERMS** RF-EMF exposure, network planning, 5G deployment, network design, multi-objective optimisation.

## I. INTRODUCTION

Deploying 5G is not just a question of financial means or installation time. Other factors also directly impact the delivery of the underlying communication technologies to the general public. An important one is about public concern on the impact of 5G on health [1]. This caused many debates, and regardless of the conclusions, it is holding back the commercial availability of 5G networks in some places, as it might in the future with the further development of this generation and 6G around 2030. The same applies to technical factors, such as energy management and security, where there are still

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significant unresolved challenges. Finally, regulatory factors are also slowing down the deployment and adoption of these networks. This paper focuses on these factors specifically.

Radio frequencies (RFs) are in the centre of the electromagnetic spectrum, which varies from electricity ranges to visible light, and nuclear radiation. The applications of RFs include radio communications and mobile networks. The prevalence of wireless communication devices has become an irreplaceable part of our daily lives, and it is pivotal to assess RF-EMF exposure when deploying new cellular technologies. Deploying 5G and future generation networks will involve deploying new base stations, transmitters, and radio equipment. In a context where many sources of RF-EMFs already exist, there is a growing concern that the limits on maximum EMF levels established by regulations will severely constrain the planning of networks in the future.

The assessment of EMF compliance has always been a significant challenge for deploying new cellular communication technologies. Moreover, whenever there is a change in cellular network generation, for example, as was seen during the 3G to 4G migration, the deployment of new networks is challenging, as it requires matching the regulatory framework to new technical needs [2]. As with previous generations of cellular networks, new 5G deployments will therefore have to comply with the relevant regulations on RF-EMF exposure, which impose strict emission limits [3]. In Europe, the regulations proposed by the International Commission on Non-ionizing Radiation Protection (ICNIRP) have been adopted [4]. The International Labour Organization (ILO) and the world Health Organization (WHO) formally recognises the ICNIRP, which also collaborates with other bodies like the EU Commission. The ICNIRP first published their recommended guidelines in 1998, and several European countries quickly incorporated them into their legislation (e.g., 1999/512/EC for general public exposure). These guidelines identify emission levels that cannot be exceeded based on well-established health considerations.

Despite the excitement surrounding 5G, which can generate massive economic output [5], exposure assessment still needs to be fully addressed. The conventional methods used to evaluate the compliance of 2G, 3G and 4G base stations are not suitable for 5G, and will likely not be well suited for future evolutions, due to active antenna technologies such as Massive MIMO with precise beamforming and TDD. Ensuring consistency between the technical requirements of 5G and current EMF regulations is of significant importance in Europe since any discrepancies could restrict or even prevent the deployment of these technologies. The International Telecommunication Union (ITU) has, for instance, called for European case studies into the possible impact of national legislation on the introduction of new 5G networks [6]. However, with a few exceptions, most countries have made little progress in assessing EMF compliance methodologies [7], as of 2021 when this study was mainly conducted.

**FIGURE 1.** Approach of this paper.

While many studies have already looked at the measurement of EMF levels in cellular networks [8], only a few have considered the dynamics of 5G base stations. The influence of limit levels on deployments, the complexity of network planning and the optimisation of deployment choices according to application, technical and regulatory needs are all aspects for which formal answers need to be formulated and standardised.

This survey attempts to consolidate the significant elements from the prior art to understand how to assess EMF exposure in cellular networks, the regulatory parameters, and the possible ways to address the new technologies required by 5G. Beyond this, this survey focuses more broadly on network planning approaches. Network planning is an essential step in implementing a communication network, and it is becoming more and more complex as it requires considering regulatory, technical and commercial elements. This survey gives an overview of popular network planning approaches, including a series of multi-objective optimisation and multi-criteria decision-making techniques to improve the positioning of antennas and demand support problems.

We divide this survey into five main technical sections to best classify the identified literature, as described in the figure below. Section II first introduces the fundamentals of cellular communications and 5G technologies to give a comprehensive background to all readers without prior technical knowledge in this area. Section III then presents the regulatory constraints at the international, European, and national levels, taking Luxembourg as example. Then, Section IV focuses on conventional exposure estimation methods (i.e., mainly standardised and in use until 5G) before presenting and comparing in Section V new methods from the scientific literature dedicated to active antennas, i.e., implementing Massive MIMO technology with precise beamforming. Finally, we change the scale of the study by discussing in Section VI the challenges related to network planning and potential solutions that make use of optimisation approaches.

The literature presented was mainly retrieved via conventional scientific search engines. The list of references is not exhaustive but representative of the most popular approaches.

## II. FUNDAMENTALS OF CELLULAR COMMUNICATIONS AND 5G

### A. HISTORY OF CELLULAR COMMUNICATION TECHNOLOGIES

Unlike other communication technologies, cellular networks are organised in generations, making it easier to coordinate standardisation efforts worldwide.

The first generation was far from being internationally standardised and consisted essentially of an analogue telephone system. This system first started to be deployed in the 1980s in cars, through devices similar to the landline phones of the time, and with ten times the transmitting power of today's smartphones for reaching 100 km away antennas [9].

The second generation, or 2G, marked the advent of mass-market mobile telephony with GSM (Global System for Mobile Communications). The telephone became a portable device used only for making calls. The throughput was limited by extracting the lowest and highest tones, thus increasing the number of simulated users. The antenna power was reduced, thus leading to an increase in antennas to cover any territory where customers were likely to move. The difficulty at that time was also to switch antennas when moving (handover). In the GSM system, the mobile terminal automatically connects to the antenna with the strongest signal.

2G was improved over time, increasing the number of antennas and offering the possibility to send data in addition to voice - but with minimal throughput, about a million times lower than 5G. The intermediate generations were GPRS (General Packet Radio Services) and EDGE (Enhanced Data Rates for GSM Evolution), which are still present in 2021 in some areas with inadequate coverage.

3G came with better throughput and more data usage than the previous generation, which focused more on voice communication. This generation sees the birth of intelligent devices with applications that generate more and more data. It is also the first generation that comes with a unified vision and global standards. Like 2G, 3G experienced several versions: UMTS (Universal Mobile Telecommunication System, in Europe), HSPA (High-Speed Packet Access) and HSPA+.

4G, via LTE (Long Term Evolution), uses a single communication channel, combining voice and data. The data rate also increases significantly, paving the way for a multitude of new connected applications. Since 4G, the main evolution has been 4G-Advanced, allowing for higher speed and reliability. As before with previous-generation technologies, the number of antennas increased dramatically - thus creating additional deployment issues such as interferences (i.e., the superposition of two signals of the same frequency). However, even with these issues and the need to manage frequency distribution, designers have opted for smaller and smaller cells - intending to reduce transmission power (and therefore EMFs) while increasing throughput.

### B. THE FIFTH GENERATION (5G)

ITU defines an Advanced Antenna System (AAS) as a collection of technologies for enhancing wireless communication in terms of data rate, user terminals, coverage and throughput [10], [11]. These technologies are related to the fifth generation (5G) standard for mobile networks defined by the 3rd Generation Partnership Project (3GPP). AASs include an AAS radio and the related AAS features (techniques and algorithms). An AAS radio is an antenna array which integrates the hardware and the software needed to transmit and receive radio signals. This integration enables new features, like spatial multiplexing and precise beamforming. It is the reason for 3GPP defining AAS as "Active" Antenna Systems instead of "Advanced", as suggested by ITU. In contrast, non-advanced antenna systems typically consist of a remote radio and a passive antenna, which is not integrated into the radio and does not execute any feature. Another criterion to separate traditional antenna systems from AAS is the number of radio chains (a single radio and its supporting architecture, like mixers, amplifiers, and analogue/digital converters). The lower boundary for the number of radio chains of an ASS is commonly 8 and 2, 4, and 8 for older systems. However, the plan for 5G is to go from 128 to 256 integrated antennas, together with more than 64 integrated transceivers combined into one system.

A Base Station (BS) is a fixed transmission and reception location in charge of handling radio traffic. It usually consists of one or more receive/transmit antennas, microwave dish and electronic circuitry. User Equipment (UE) is any device employed by an end-user to communicate with a BS (e.g., a smartphone). An air interface is the radio portion of the circuit between the UEs and the active BS. 3GPP defined 5G New Radio (NR) as the new air interface for 5G. The concept of 5G NR is closely related to the rest of the 5G technologies like Massive MIMO and precise beamforming, allowing signals to utilise space more efficiently.

Beamforming is a technique for directional signal reception or transmission. Generalised beamforming sends the same data stream in several different paths (direction and polarisation). The technique controls the phases and amplitudes of the data streams to add them constructively at the receiver. This method is beneficial when a direct path is not available. Multiple propagation paths are generated through the radio channel, from the transmitter to the receiver facing diffraction and reflections from buildings and other constructions. With null forming, it is also possible to reduce the interference with other UEs by controlling the transmitted signals to cancel each other out at the receiving end.

MIMO or spatial multiplexing is a method for transmitting more than one beam simultaneously using the same time and frequency resource, employing beamforming. This technique is known to previous generations, but the introduction of AAS in 5G enables more advanced MIMO methods. Single-User MIMO (SU-MIMO) transmits data in multiple beams, called layers, from the AAS to an individual UE, thus increasing the throughput. The number of layers that a system can use is called the rank and depends on the radio channel. To distinguish among a certain number of layers, a UE needs to have at least the same number of receiver antennas. SU-MIMO is able to operate with different layers towards the same direction with different polarisations or different propagation paths with similar strength. In Multi-User MIMO (MU-MIMO) or Massive MIMO, the AAS increases the network capacity by simultaneously sending different layers to different users in separate beams using the same time and frequency resources. MU-MIMO is possible only when the system finds at least

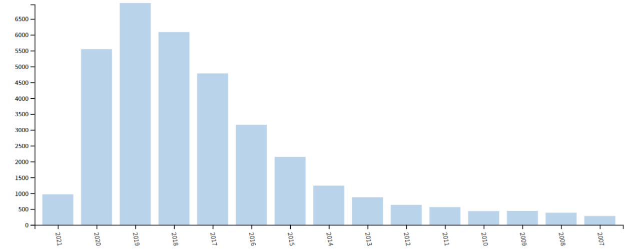

**FIGURE 2.** Publications by year using the keyword “5G”.

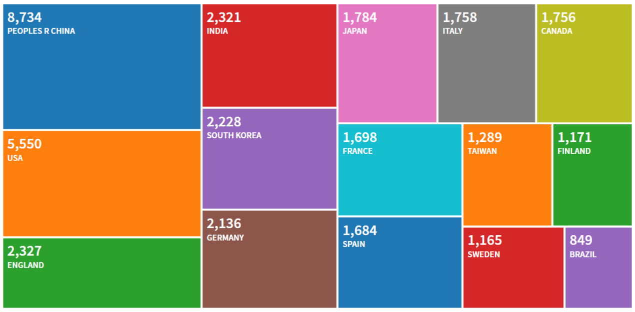

**FIGURE 3.** Publications by country using the keyword “5G”.

two users who want to send and receive data simultaneously. Also, for the sake of efficiency, the interferences between several users should be minimised. This can be done using several techniques such as generalised beamforming with null forming.

4G and previous generations employ different frequencies to transmit or receive information between the UEs and the BS. This technique is known as Frequency Division Duplex (FDD). 5G proposes a Time Division Duplex (TDD) instead, where both uplink and downlink use the same spectrum frequencies but at different moments in time. In this scenario, the operator is the one who defines how the 5G antennas adapt over time (e.g., in Luxembourg, operators consider 25% uplink and 75% downlink).

5G also achieves an increased end-user throughput by using higher frequencies with shorter range than previous generations. A 5G network will be composed of different types of cells (e.g., small cells vs macrocells), each requiring particular antenna designs and providing a different trade-off between download speed and distance. The faster 5G cells employ an RF band from 30 to 300 GHz, which the ITU defines as Extremely High Frequency (EHF), or millimetre waves (mmWave).

### *C. 5G AND EMF EXPOSURE IN THE SCIENTIFIC LITERATURE*

According to the Web of Science database,[1] many articles related to 5G and EMF exposure/emissions have obviously been published in the literature since 2007. It should be noted that this section is only focused on a few specific keywords

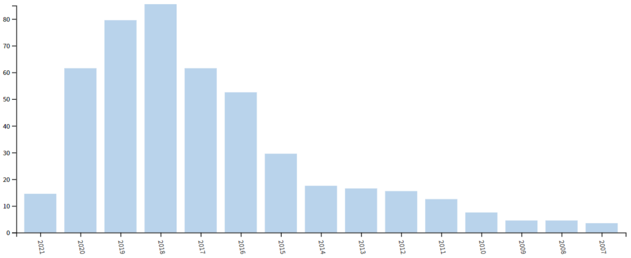

**FIGURE 4.** Publications by year using the keywords “5G” and “emission”.

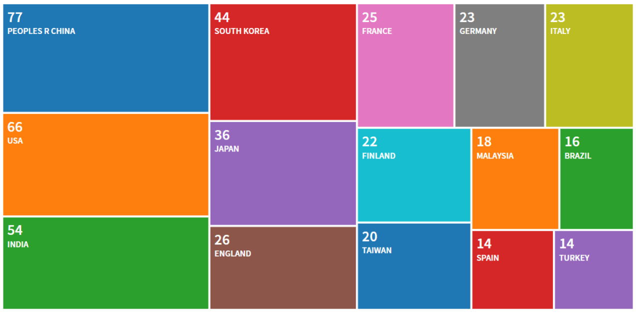

**FIGURE 5.** Publications by country using the keywords “5G” and “emission”.

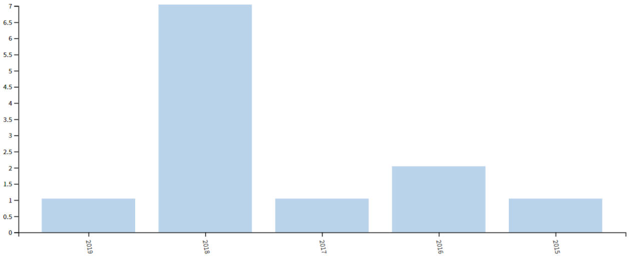

**FIGURE 6.** Publications by country using the keywords “5G”, “emission”, “simulation”, “optimization”.

and should not be interpreted as a general fact. The idea is to showcase the proportion of research interest for this survey’s topics.

Figure 2, for instance, illustrates the distribution of 35,808 recorded publications with the keyword “5G”. Regarding the geographical contributions on the topic, Figure 3 shows research activities that have taken place in different countries – showing a more important number of publications in China and US.

On the other hand, narrowing it down into 5G-related publications with the keyword “emission” dramatically reduces the number of results to 489, as illustrated in Figure 4 and Figure 5, and even if this number is likely to evolve quite quickly in the next coming months and years given the importance of the topic.

Considering the solution approaches reviewed in this survey, the investigation into the keywords “simulation” and “optimization” emphasises a significant gap between publications and 5G-related research. For instance, 90 publications

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[1] https://www.webofknowledge.com/

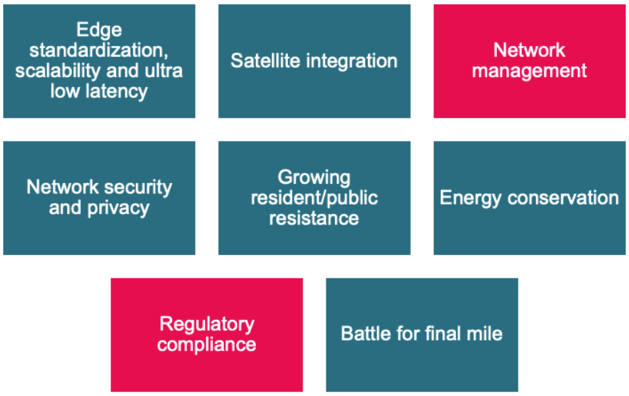

**FIGURE 7.** Key challenges related to 5G and beyond networks that have been identified by IEEE Future Networks. The red items are covered in this survey.

contain the keywords "5G", "emission", and "simulation". However, if the keyword "optimization" is in this list, only 12 papers (Figure 6) appear in the literature, thus signifying once more the importance and potential of these techniques.

### *D. BIG CHALLENGES RELATED TO 5G*

Figure 7 shows the main challenges related to 5G and future generation networks that the IEEE Future Networks Community has identified through its International Network Generations Roadmap (INGR) [12]. The goal of INGR is to "help guide operators, regulators, manufacturers, researchers, and other interested parties involved in developing 5G and Beyond communication technology ecosystems by laying out a technology roadmap with 3, 5 and 10-year horizons".

Among these challenges, three are of particular interest and will be directly impacted by the directions and topics that have been identified in the present paper:

- **Direct challenge: network management**. According to IEEE, this challenge mainly involves artificial intelligence and machine-learning approaches, which are "needed to address various network management issues such as resource allocation, routing, cross-layer optimisation, mobility, and handover decisions". This challenge is also related to network planning and design, which was previously very important in network management, as highlighted in the previous section.
- **Direct challenge: regulatory compliance**. In addition to the technical challenges described in this paper regarding EMF compliance, according to IEEE, there is a growing concern that other limiting factors will be established, such as limiting the power of RF transmissions based on safety or noise level. The potential optimisation approaches to be proposed for EMF-aware network planning solutions are a first basis that could then be adapted with additional constraints.
- **Indirect challenge: growing resident/public resistance**. There are still many communities worldwide that are resisting the installation of 5G antennas in their neighbourhoods. Public awareness and decision-support systems are key to face this challenge.

Figure 8 shows the key topics surrounding 5G. They are wide-ranging and cover security issues, satellite connectivity, energy management and other topics like standardisation aspects. EMF management is linked to at least four of these topics, which speak for themselves: wireless analytics (or more generally the use of AI for analysing network signals), deployment issues, Massive MIMO, and system optimisation approaches. This statement is high level and relatively evident. However, it shows the interest and multiple possibilities about EMF-aware network planning - which is not a niche, but a topic with significant potential, including in a few markets.

## III. REGULATORY FRAMEWORK

With the progress made in communication technologies, the general public is becoming increasingly apprehensive of the emergence of possible new risks to which the population and the environment are exposed. Concerns about potential adverse health effects caused by RF-EMFs (100 kHz - 300 GHz) led authorities to introduce precautionary exposure limits, varying considerably between regions. Measures based on the "precautionary principle" have to be proportional to the level of protection, knowing that zero risks can rarely be achieved. Therefore, practical measurements of the EMF and the exposure to the 5G network are essential to both 5G network deployment and compliance with the regulations. Thus, we review the limits introduced at the international level in this section, mainly from the ICNIRP guidelines and compare them with the EU recommendations and the Luxembourgish limits.

### *A. INTERNATIONAL LEVEL*

The guidelines produced by ICNIRP for EMF exposure (up to 300 GHz), which apply to occupational and general public exposure, were first published in 1998 to prevent known adverse health effects [4]. The occupational exposure concerns adults who are exposed, under known conditions and with the necessary knowledge/training (e.g., a professional environment), while the general public exposure includes all individuals who are not necessarily aware of EMF exposure. These considerations imply adopting stricter restrictions for the general public than for the occupational population. The ICNIRP guidelines take into consideration the exposure of the general public, as well as exposure in workplaces. Radiation limits are usually specified by an electric field E expressed in V/m or by a power flux density P expressed in W/m [13]. The link between these two values can be expressed as defined in Equation 1.

$$P = \frac{E^2}{376,73} \tag{1}$$

After a careful review of published scientific literature and in order to apply restrictions based on the assessment of

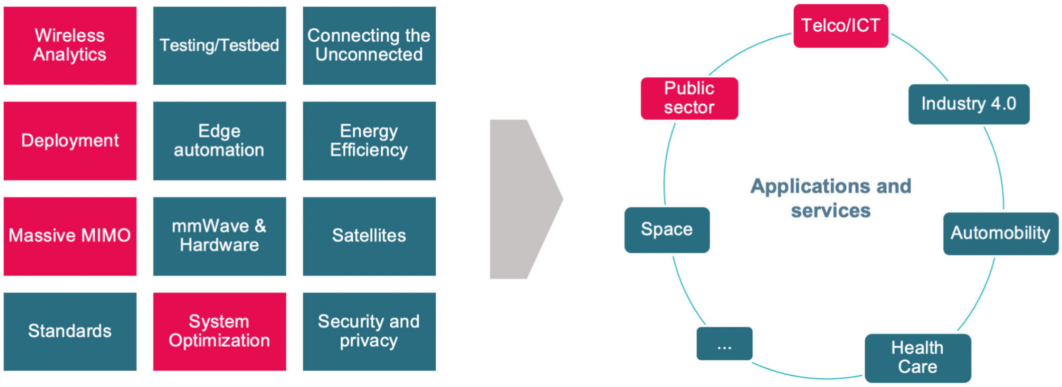

**FIGURE 8.** Key topics and applications. The red items are covered in this survey.

health effects of electromagnetic fields, ICNIRP has developed two types of restrictions:

1) **Basic restrictions**. These are defined as "restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields, which are based directly on established health effects and biological considerations" [4]. The basic restrictions are defined as internal measures of exposure in terms of a biologically effective quantity [14]. The physical quantities used to specify these restrictions are the current density (J), specific energy absorption rate (SAR), and power density (S). It should be noted that only power density in the air outside the body could be readily measured in exposed individuals. The interested reader can refer to [4] for more information - these values not being the core focus of this survey.
2) **Reference levels for limiting exposure**. These are measures related to the internal measures of exposure and expressed in terms of directly measurable quantities of external exposure. These reference levels are defined as "levels which are provided for practical exposure-assessment purposes to determine whether the basic restrictions are likely to be exceeded" [4]. The reference levels are physical quantities that are stricter than the fundamental restriction to avoid potential risks but are also easier to measure and assess. Some reference levels are derived from relevant basic restrictions using measurements and computational techniques, and others address perception and adverse indirect effects of exposure to EMFs. Hence, basic restrictions are closely related to biological mechanisms, while reference levels are easier to evaluate. The use of reference power levels permits compliance with basic restrictions on exposure since the relationships between them have been developed for situations of maximum coupling conditions between fields and exposed people [14]. If the power levels of reference are exceeded, basic restrictions are not necessarily compromised. The ICNIRP reference levels of occupational and general public exposure are presented in Table 1. In this table, the electric field strength (E), magnetic field strength (H), magnetic flux density (B), and equivalent plane wave power density (Seq) are presented at frequencies between 0 Hz and 300 GHz.

Exposure limits in various countries can be found online on the WHO website [15].

### B. EUROPEAN LEVEL

The council of the European Union has published Recommendation 1999/519/EC of 12 July 1999, including frequency-dependent reference levels for general public exposure, which are considered as limit values. These limits are identical to the ICNIRP limit values for general public exposure. However, for frequencies between 0 and 1 Hz and the current density, the elemental restrictions from the EU council consider the magnetic flux. Many European countries implemented these recommendations, and thus the ICNIRP guidelines, in their legislations. However, some countries like Italy or Luxembourg adopted legal regulations for human and environmental protection against the influence of EMF. In some cases, these regulations are stricter than the EU recommendations.

Additionally, the reference levels for general public exposure from the EU Council recommendations are EMF values intended to be averaged both over space and over six minutes, following ICNIRP Guidelines.

RF reference levels are defined by key metrics, such as the Root Mean Square (RMS) value of the electric field (E) in V/m and the power density (S) in W/m2. The RMS limit values, set by ICNIRP and featured in the 1999/519/EC recommendation, are listed in Table 2.

These levels are provided as comparison values for the measured quantities and should be considered to respect the primary restriction. In this regard, for evaluating the compliance of the reference levels with the basic restrictions, any existing European or national standards, which are based on scientifically proven measurement and calculation procedures, should be considered. Additionally, criteria like

**TABLE 1.** ICNIRP reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed RMS values).

| Exposure characteristics | Frequency range | E-field strength $(V/m)$ | H-Field Strength $(A/m)$ | B-field $(\mu T)$ | Equivalent plane wave power density Seq $(W/m^2)$ |
|---|---|---|---|---|---|
| **Occupational exposure** | Up to 1 Hz | - | $1.63 * 10^5$ | $2 * 10^5$ | - |
| | 1 to 8 Hz | 20000 | $1.63 * 10^5/f^2$ | $2 * 10^5/f^2$ | - |
| | 8 to 25 Hz | 20000 | $2 * 10^4/f$ | $2,5 * 10^4/f$ | - |
| | 0,025 to 0,82 KHz | $500/f$ | $20/f$ | $25/f$ | - |
| | 0,82 to 65 KHz | 610 | 24.4 | 30.7 | - |
| | 0,065 to 1 MHz | 610 | $1.6/f$ | $2/f$ | - |
| | 1 MHz to 10 MHz | $610/f$ | $1.6/f$ | $2/f$ | - |
| | 10 to 400 MHz | 61 | 0.16 | 0.2 | 10 |
| | 400 to 2000 MHz | $3 * f^{0,5}$ | $0.008 * f^{0,5}$ | $0.01 * f^{0,5}$ | $f/40$ |
| | 2 to 300 GHz | 137 | 0.36 | 0.45 | 50 |
| **General public exposure** | 0 to 1 Hz | - | $3.2 * 10^4$ | $4 * 10^4$ | - |
| | 1 to 8 Hz | 10000 | $3.2 * 10^4/f^2$ | $4 * 10^4/f^2$ | - |
| | 8 to 25 Hz | 10000 | $4000/f$ | $5000/f$ | - |
| | 0,025 to 0,8 KHz | $250/f$ | $4/f$ | $5/f$ | - |
| | 0,8 to 3 KHz | $250/f$ | 5 | 6.25 | - |
| | 3 to 150 KHz | 87 | 5 | 6.25 | - |
| | 0,15 to 1 MHz | 87 | $0.73/f$ | $0.92/f$ | - |
| | 1 to 10 MHz | $87/f^{0,5}$ | $0.73/f$ | $0.92/f$ | - |
| | 10 to 400 MHz | 28 | 0.073 | 0.092 | 2 |
| | 400 to 2000 MHz | $1.375 * f^{0,5}$ | $0.0037 * f^{0,5}$ | $0.0046 * f^{0,5}$ | $f/200$ |
| | 2 to 300 GHz | 61 | 0.16 | 0.20 | 10 |

duration of the exposure, exposed body parts and the age and health status of the general public could be taken into account in all countries.

Comparing the EU recommendations with the ICNIRP guidelines, the basic restrictions and reference levels are defined identically in the ICNIRP and EU recommendations.

As briefly mentioned above, because EU recommendation 1999/519/EC on the boundaries of exposure of the public to electromagnetic fields is not legally binding, we observe that the EMF policy in the EU countries can be organised into the following levels:

- **Level 1**: EU recommendations, which purpose is to unify the countries' legislations. Hence, the restriction and reference levels from the EU recommendations (and the 1998 ICNIRP Guidelines) must be applied. This level is applied in Czech Republic, Estonia, France, Greece, Hungary, and Ireland.
- **Level 2**: The EMF limits of each country based on the EU recommendations or ICNIRP guidelines are not legal requirements. The limits are either less strict or not regulated. It is, however, possible that the authorities or the companies apply the EU recommendations in practice. Examples of EU member states applying this level are Cyprus, Denmark, Finland, Latvia, Malta, the Netherlands, Spain, Sweden and the United Kingdom [16].
- **Level 3**: Stricter basic restrictions and reference levels than those of the EU recommendations are based on the preventive principle. Examples of regions applying this level, as of 2021, are Luxembourg, Poland, Italy, Switzerland, Paris, and regions of Belgium.

### C. LOCAL LEVEL – LUXEMBOURG

The exposure levels in Luxembourg are those set out by EU recommendations (hence the ICNIRP Guidelines). Based on the EU recommendations, the limits of cumulated exposure levels vary between 38 and 61 V/m depending on the frequency (see Table 3).

However, concerning risk reduction, few additional measures were considered in the precautionary principle use. In fact, according to the European comission on the precautionary principle COM(2000) [17], every member state has "the right to establish the level of protection - particularly of the environment, human, animal and plant health - that it deems appropriate". Its political responsibility consists of defining the "acceptable" level of risk for its society. These measures should be proportional, non-discriminatory based on examining the potential benefits and costs and subject to review. The proportional application of the precautionary principle means that measures taken should allow an appropriate level of protection without causing an unjustified burden to the addressees. It does not mean that risks based on any technology must be reduced to zero. On the contrary, zero risks are only very rarely achievable.

Site permit requirements are derived, among others, from a law commonly referred to as "loi Commodo" [18], regulating the integrated prevention and reduction of pollution, public safety, hygiene and comfort and the promotion of

**TABLE 2.** Reference levels of electric, magnetic and electromagnetic fields (0 Hz to 300 GHz, unperturbed RMS value).

| Frequency range | E-field strength $(V/m)$ | H-Field Strength $(A/m)$ | B-field $(\mu T)$ | Equivalent plane wave power density Seq $(W/m^2)$ |
|---|---|---|---|---|
| **0 to 1 Hz** | - | $3.2 * 10^4$ | $4 * 10^4$ | - |
| **1 to 8 Hz** | 10000 | $3.2 * 10^4/f^2$ | $4 * 10^4/f^2$ | - |
| **8 to 25 Hz** | 10000 | $4000/f$ | $5000/f$ | - |
| **0,025 to 0,8 KHz** | 250/f | 4/f | 5/f | - |
| **0,8 to 3 KHz** | $250/f$ | 5 | 6.25 | - |
| **3 to 150 KHz** | 87 | 5 | 6.25 | - |
| **0,15 to 1 MHz** | 87 | $0.73/f$ | $0.92/f$ | - |
| **1 to 10 MHz** | $87/f^{0,5}$ | $0.73/f$ | $0.92/f$ | - |
| **10 to 400 MHz** | 28 | 0.073 | 0.092 | 2 |
| **400 to 2000 MHz** | $1.375 * f^{0,5}$ | $0.0037 * f^{0,5}$ | $0.0046 * f^{0,5}$ | $f/200$ |
| **2 to 300 GHz** | 61 | 0.16 | 0.20 | 10 |

**TABLE 3.** Maximum value of the cumulated electric field for specific frequencies in accordance with the EU recommendations applied in Luxembourg.

| Frequency band [MHz] | Technology | Maximum value of the cumulated electric field [V/m] | Maximum value per radiating element [V/m] |
|---|---|---|---|
| 700 | LTE/5G | 38 | 3 |
| 800 | LTE | 39 | |
| 900 | GSM | 41 | |
| 1800 | LTE | 56 | |
| 2100 | UMTS | 61 | |
| 2600 | LTE | 61 | |
| 3600 | 5G | 61 | 3 (max crest-factor: 2; max-hold $<$ 6 V/m) |

sustainable development. Radioelectric sites are permit-free or can be classified into two types of permitting procedures. The permit type depends on the sum of all antenna input power ($P_{in}$) installed on the same radioelectric site [19]:

- If the sum of all antenna input power for mobile communications installed on the same site is below 50 W ($\sum P_{in} < 50$ W/per site), the site is exempt from a permit obligation.
- If the sum of all antenna input power is greater than or equal to 50 W and inferior to 2,500 W (in case of a non-stand-alone installation), the antenna site is classified in class 3.
- Otherwise, if the sum of all antenna input power is greater than 2,500 W, the antenna site is classified as Class 1, meaning that a public enquiry is needed before the decision is made to evaluate whether a permit is granted or not.

These permits comprise the installation and operating conditions deemed necessary to ensure compliance with the essential requirements of the aforementioned “loi Commodo”. Therefore, a permit is only delivered after the authorisation request has been thoroughly examined, including field strength simulations proving compliance with regulatory limits.

In order to limit the risks, reduced exposure levels generated by radio communication base stations have been defined. Luxembourg adopted stricter electromagnetic exposure levels than those indicated in the 1999/519/EC Recommendation. These stricter, lower human exposure levels in the bandwidth used for mobile communication (700 MHz – 3,600 MHz) consist of a maximum contribution to the general electric field of 3 V/m (maximum value) per radiating element, which depends on the considered transmitter technology. This regulation is applied indoors, in places where humans usually spend long periods, formally defined by general land use plans as homes, schools, hospitals, health and care homes, offices, workplaces, private and public playgrounds. Balconies, terraces, roads, sidewalks, gardens, parks are not included in these places and are not subject to these limits.

In the Grand Duchy of Luxembourg [20], when several elements radiate in the same direction, the maximum value of the cumulated EMF (in V/m) is calculated with the Equation 2, where $n$ is the number of radiating elements in one direction.

$$E_{max} = 3 \cdot \sqrt{n} \tag{2}$$

As described above and under ICNIRP guidelines, the EMF exposure is averaged over six minutes (brief exposure), using the RMS value of the electric field. In the case of 5G, as of April 2021, two frequency bands are considered in Luxembourg:

- In the low frequency 700 MHz band, antennas have no new specific requirements, and the current methodology is retained. Therefore, the limit value remains 3 V/m per radiating element in places where people stay for longer periods.
- In the case of the 3,600 MHz band and the use of Massive MIMO antennas, 3 V/m is still the reference, averaged over 6 minutes (RMS), but with a maximum crest-factor of 2 (max-hold < 6 V/m) in places where people

stay for longer periods. This factor (also called peak-to-average ratio) is the difference between the average and peak signal value. Increasing it makes it easier to deal with the dynamics associated with 5G antennas, transmitting multiple carriers simultaneously and making the old single-carrier methods inoperable. In cases where deployment is critical, the use of max peak power limitation or power control tools, as suggested by [21] could be considered, as well as attenuation factors as defined by [22]. This methodology is an evolution in the years considering the current research and measurement campaigns carried out.

This reduced exposure level is only applied for mobile communication antenna sites that need a permit. In the framework of this permit, classified establishment authorisations have set the maximum value for the contribution of each radiation element from the mobile phone base stations significantly lower than the values in the EU Council recommendation. The contribution to the total field level is set to 3 V/m per radiating element, which corresponds to 7% of the cumulated European threshold for the 900 MHz frequency band. Following this restriction, after receiving permission, the operator have to install antennas guarantying a maximum electric field strength of 3 V/m per radiating element. Hence, even with fewer electromagnetic wave emitters installed on a site, the result of the accumulated fields at a given emission point should remain significantly below the reference level recommended in Europe. For example, for six transmitters, emitting in maximum authorised power mode, in the same direction, with the same antenna pattern, with identical signal characteristics, the resultant is calculated as $3 \times \sqrt{6} = 7.3\frac{V}{m}$. In addition, it should be noticed that this limit provides additional safety to the safety coefficient of about 50% below the threshold values for the appearance of acute effects and the fundamental restriction values that implicitly cover the possible long-term effects over the entire frequency range.

Furthermore, contrary to some other EU countries (e.g., Belgium, Italy, and Poland), and as of 2021, Luxembourg does not consider cumulative limit values; instead, the limitation is imposed on one radiating element.

### *D. ASSESSMENT METHODOLOGY IN LUXEMBOURG*

In Luxembourg, regardless of the communication technology, calculations are first performed through software provided by the Institut de Sciences Sociales, Economiques et Politiques (ISSeP). This software simulates electromagnetic waves' propagation and graphically displays the antenna lobes and their electric fields at a given frequency, power, heights, distance, and inclinations. These simulations make it possible to change various input powers and input parameters and evaluate on the fly their impacts on the EMF limits while considering the surrounding living and working areas.

At a later stage in the process, called reception, and once the antennas are physically installed, a monitoring report is prepared by ISSEP with actual measurements to ensure that the predicted/simulated of the installed antennas comply with the EMF limits. These measurements are made using equipment, including a frequency-selective measurement device and three-axis measuring antennas for electric fields.

According to ISSeP's report 1709/2009 [23], ISSeP applies a measuring method to carry out the reception and in situ inspection of electromagnetic wave transmitters under the labour and mining inspectorate in the Grand Duchy of Luxembourg (ITM-CL 179.4). The method used provides a result independent of the radiated power at the time of the measurements. The intensity of the electromagnetic radiation obtained is the maximum possible field strength reached at the location under consideration when the antenna is transmitting at maximum power. As of 2021, the measuring methods are mostly based on static antenna patterns, whereas 5G antennas are dynamic. Therefore, it is necessary to revise the current EMF measuring techniques to assess the exposure resulting from 5G antennas.

As highlighted by [2], further aspects might be necessary for a good EMF estimation, such as the use of digital maps with precise grids (i.e., 1m x 1m). Since September 2017, a wireless cadastre of base stations for public mobile communication networks has been made accessible online via the Luxembourgish Geoportal [24]. This website displays a country map, including each base station's location and technical characteristics, which might help to build realistic simulation scenarios. The wireless cadastre represents the locations and operating licences for classified GSM transmitting antenna establishments operating in the frequency band between 791 MHz and 2690 MHz. In addition, the map shows the geographical information on the locations and the technical information relating to the transmitting antennas following Article 9 of the Grand-Ducal Regulation of 25 January 2006.

### *E. SUMMARY OF THIS SECTION*

This section reviews the regulations on EMF exposure that apply globally and in Europe, focusing on the situation in Luxembourg - which has more substantial exposure limits. In the EU, each country is free to set its regulations. However, most of them follow the European guidelines derived from the ICNIRP recommendations at the global level. In radio frequencies, the regulatory limits are measured in V/m. The assessment measures in place require determining a maximum value (i.e., worst-case scenario) entirely independent of fluctuations in the antenna's usage. In Luxembourg, the threshold value is 3 V/m for each radiating element.

## IV. RF-EMF EXPOSURE ASSESSMENT, PART 1: CONVENTIONAL METHODS AND STANDARDS

RF-EMF exposure assessments are conducted to ensure that base stations comply with regulatory requirements on exposure before being installed and launched on the market. This section successively describes the conventional methods used for 4G and previous generation networks. It then focuses on the impact of new active antenna technologies and the needs and contributions from the literature.

### A. KEY PARAMETERS AND PERFORMANCE INDICATORS

Before discussing EMF exposure estimation methods, it is important to first start by introducing key definitions and the main parameters and metrics that play a role in such methods. The first concept that gives an easy understanding of several factors is the radiation (or emission) pattern of an antenna (be it 5G or not), graphically representing the antenna radiation in three dimensions. The energy emitted by an antenna is distributed unequally in space, with particular directions being favoured: these are the radiation lobes. The horizontal (viewed from above) and vertical (viewed from the side) planes of the radiation pattern always include the most prominent lobe. Lobes are usually displayed in 2D for the sake of readability. The main parameters that can influence the EMF exposure of a 5G installation are defined in Table 4.

The most critical performance indicator to consider in this exercise is the EMF exposure (measured in V/m) which must be aligned with the regulatory limits. If this number is not compliant, then one solution would be to reduce the transmitting power of the antennas. However, this action directly impacts the antenna's performance, including coverage, number of customers served, throughput, and quality of service. The key performance indicators that RF-EMF impacts are listed in Table 5. Finding the best configuration for an antenna, therefore, requires taking all these values into account, which increasingly justifies the implementation of optimisation systems that make it possible to achieve suitable values while respecting the existing constraints, as detailed further in Section VI.

### B. TWO WAYS: CALCULATION OR MEASUREMENT

The assessment of electromagnetic fields for exposure limits compliance is an essential exercise in network planning and deployment, requiring validation by a competent authority. Existing estimation methods have remained unchanged for many years and were very effective for communication technologies before 4G. This section describes the fundamental methods, and for each of them, their shortcomings and drawbacks - before listing more exploratory approaches via recent scientific literature. A significant part of the content described in this section is taken from Recommendation ITU-T K.91 [25], ICNIRP [26] and GSMA [27], to which the interested reader can refer for more detailed information (the main objective here being to introduce assessment principles).

Among all the assessment methods, it is generally recommended to apply the simplest one first. As described by ITU [25], these other more advanced methods should be used if the simpler ones are not shown to be compliant. In other words, if the simplest calculation method leads to non-compliance, then a more complex, and therefore accurate method is tried, and so on until the installation is deemed compliant (or conversely until the calculation methods are no longer available - in which case the installation must be configured differently). Theoretical calculations of exposure level estimates should always be designed so that the calculation leads to an overestimation of the fields.

The assessment can be done in two different ways, i.e., either by calculation (computer simulations) or by actual measurements depending on the stage of network deployment or the operator's willingness. The advantage of using simulations is that an estimate can be made quickly, cheaply and without having to deploy physical resources (test before invest), but the accuracy can sometimes be far from reality - or the models used very complex. Measurement often validates an installation and is easier to set up, but requires an established radio site. According to [28], metrics that are used for assessing exposure to RF-EMF are divided into four types: incident field metrics (e.g., E field, power density S), exposition ratios, absorption rate, and dose. This section mainly focuses on (a).

### C. FOCUS ON CONVENTIONAL APPROACHES BY MEASUREMENT

The field strength can be measured in three different ways:

- Broadband measurement: simple and accessible method but usually leads to overestimation. It is the method usually selected in the first instance.
- Frequency-selective measurement: more expensive and time-consuming method, because it requires post-processing. It is preferred for special cases.
- Code-selective measurement: spot measurements, i.e., recording the field strength at a given location and time, are fairly easy but make it difficult to extrapolate the field strength to the worst-case scenario. The measuring instrument must handle large instantaneous bandwidths and decode the signal so that extrapolation is possible. To this end, the basic principle of selective code measurement is the measurement of the received power from a constant radiofrequency source, and apply an appropriate extrapolation factor [29]. Following the European EN 50492 standard [30], the following signals are always broadcasted with constant power and are therefore used by measurement techniques:
    - 2G/GSM: Broadcast Control Channel (BCCH). The maximum value of the electric field strength in V/m can be extrapolated as $E_{max} = E_{BCCH} \cdot \sqrt{NC}$, with $E_BCCH$ the field strength measured at the frequency of the pilot signal (i.e., BCCH) and NC the number of carriers.
    - 3G/UMTS: Primary-Common Pilot Channel (P-CPICH). The maximum value of the electric field strength in V/m, can be extrapolated as $E_{max} = E_{CPICH} \cdot \sqrt{10}$. In other words, the field strength corresponding to the maximum power is based on the fact that the CPICH power is about 10% of the maximum radiated power.
    - 4G/LTE: Cell-Specific Reference Signal (CRS). The maximum value of the electric field strength in V/m can be extrapolated as $E_{max} = E_{(CRS_{max})} \cdot$

**TABLE 4.** Key parameters for estimating RF-EMF exposure.

| Name | Unit | Description | Example of value |
|---|---|---|---|
| Antenna brand and model | N/A | The antenna model can be used to determine some of the parameters listed in this table. | Huawei AAU5613 |
| Frequency | MHz | This refers to an electromagnetic wave frequency between 3 kHz and 300 GHz, which includes the frequencies used by radio communication. | 3 500 |
| Polarization | o | The polarization of radio waves received or emitted by an antenna is defined by the physical orientation of the antenna. | -45 |
| Electrical tilt | o | Inclination of the antenna to change the signal propagation in a desired direction and subsequently the radiation pattern. This is done by changing the characteristics of the signal phase and can therefore be automated/made variable remotely. | -6 |
| Antenna height | m | Height from the ground at which an antenna is installed. | 20 |
| Power / carrier | W | Average power per carrier | 30 |
| Mechanical tilt | o | Mechanical inclination of the antenna to change the signal propagation in a desired direction and subsequently the radiation pattern. | 0 |
| Iso-value | V/m | Isotropic radiation maximum value. | 3 |
| Attenuation | dB | Reduction of signal strength during transmission. | 0 |
| Number of carrier(s) | N/A | A carrier is a waveform that is modified by an input signal to carry information. In radio communications, a carrier delivers information by means of an electromagnetic wave. The presence of several carriers (e.g., using frequency division multiplexing) allows information to be delivered more efficiently. | 1 |
| Total power | W | Total power used by the antenna. This parameter is the most important since it directly influences the EMF exposure and the antenna's performances. | 30 |
| Gain in a specific direction | dBi | Describes how much power is transmitted into this direction. | 25 |
| Vertical beamwidth (3 dB) | o | Angle from which most of the antenna's power (illustrated by the main lobe of the antenna's radiation pattern - viewed from the side), radiates. | 27.1 |
| Horizontal beamwidth (3dB) | o | Angle from which most of the antenna's power (illustrated by the main lobe of the antenna's radiation pattern - viewed from above), radiates. | 107.2 |
| Horizontal angle | o | Includes all the angles. | 0 |

**TABLE 5.** Key performance indicators for assessing RF-EMF exposure.

| Name | Unit | How can we estimate it? (planification, software) | How can we measure it? (after deployment, hardware) | If applicable: is there any constraint? (e.g., regulatory framework) | If applicable: what are the strategies to reduce the constraint? |
|---|---|---|---|---|---|
| **EMF exposure** | V/m | Simulation, EMF estimation tool (e.g., iSSeP tool) | EMF monitoring device (e.g., Keysight FieldFox) | Must not exceed 3 V/m for each radiating element (Luxembourg) | Reducing the antenna's output power |
| **Accessibility** | Visual indicator | Simulation, planification tool (e.g., Frosk Atool) | RF monitoring device | N/A | N/A |
| **Mobility** | N/A | | | | |
| **Network traffic** | bit/s | | | | |

$\sqrt{K}$, where K is an extrapolation factor, which depends on the bandwidth of the signal.

If the EMF meter can capture all the frequency bands, measurements may be obtained without the knowledge of the exposure source. Nevertheless, in general, it is always advantageous to have the following data for measurements as it makes them more accurate:

- The radio frequency, to use a device with a band that covers it.
- The distance to the transmitting antenna, to have a suitable measurement procedure.
- The maximum equivalent radiated power to estimate the necessary range of the measurement equipment.
- The transmission power of the antennas at the time of the measurement.
- Modulation characteristics.

Existing measurement techniques are subject to international standardisation. The International Electrotechnical Commission (IEC) has recently published [21] and [31], which details these techniques. EMF measurements can be combined with theoretical models for the optimisation and validation of the exposure.

There are many devices on the market, but several conditions must be met in our case. Firstly, these devices must be calibrated appropriately - for example, according to ISO/IEC 17025 on "general requirements for the competence of testing and calibration laboratories". Secondly, they must be compliant with the regulations in force in the country of measurement and respect the procedures in place – [23] and [30] for example, in Luxembourg. Finally, in the context of 5G, they must consider the signal's dynamics. Otherwise, an overestimate may be derived.

### D. FOCUS ON CONVENTIONAL APPROACHES BY CALCULATION

In all cases, assessing exposure by calculation requires information on the radiating sources. In general, the more data the model contains, the more accurate it is, as shown incrementally below. The interested reader can refer to [25] and [32] for more details.

#### 1) POINT SOURCE MODEL WITH ISOTROPIC ANTENNA

As a minimum, the data needed for the calculations (which leads to the most conservative approach) are:

- The frequency carrier
- The distance between the user and the antenna,
- The maximum Equivalent Isotropic Radiated Power (EIRP), which is the maximum amount of power (W) that could be radiated from an isotropic antenna (theoretical model that radiates uniformly in all directions).

To measure it, one can use point source model with isotropic antenna. This method is one of the simplest to implement since it is mostly based on the maximum EIRP. It has the disadvantage of providing a big overestimate, equivalent to a free-space propagation loss, but can be generalised to most of the cases. The maximum value of the electric field strength $E_{\max}$, in V/m, can be estimated with the following equation:

$$E_{\max} = \frac{\sqrt{30 \cdot EIRP}}{r} \tag{3}$$

- r [m]: the distance between the investigation location (i.e., the user) and the antenna
- EIRP [W]: the Equivalent Isotropic Radiated Power

#### 2) POINT SOURCE MODEL WITH RADIATION PATTERN

If data on the radiation patterns of the transmitting antenna are available, a more advanced model can be used:

$$E_{\max} = \frac{\sqrt{30 \cdot P \cdot G}}{r} \cdot f(\theta, \varnothing) \tag{4}$$

- r [m]: the distance between the investigation location (i.e., the user) and the antenna
- P [W]: the input average power
- G [dBi]: the maximum gain of the transmitting antenna
- $f(\theta, \varnothing)$: the relative antenna amplitude radiation pattern - $\theta$ the azimuth and $\varnothing$ the elevation angle

#### 3) SYNTHETIC MODEL

Many antennas are built with systems that contain many identical radiating elements. In this case, additional data can be considered, thus leading to the synthetic model.

$$E_{\max} = \sum_{n} \alpha_n \frac{\sqrt{30 \cdot P_n \cdot G_n}}{r_n} \cdot e^{j(\gamma_n + \frac{2\pi r_n}{\lambda})} \tag{5}$$

- r [m]: the distance between the investigation location and the centre of the n-th panel
- $P_n$ [W]: the transmitting power to n-th panel
- $\gamma_n$ [rad]: the relative phase of applied voltage at n-th panel
- $G_n$ [dBi]: the n-th panel gain in relation to an isotropic antenna towards the user.
- $\alpha_n$: a weighting coefficient

#### 4) FULL-WAVE METHODS

Additional and more accurate data can be used if the previous models result in non-compliance or are deemed unsuitable. This data contains for example the precise position of each metal of the antenna. This would allow the implementation of full-wave methods such as the Method of Moments (MoM) or the Finite Difference Time Domain (FDTD). Additional details on the calculation methods can be found in standards [6].

#### 5) USAGE AND COMPARISON

The selection of these methods depends on several factors [32]:

- The field area where the exposure assessment is performed, i.e., near-field or far-field area. The far-field area corresponds to all the cases considering the distance from the transmitting antenna is bigger than: $\max\left(3\lambda, \frac{2D^2}{\lambda}\right)$, with $D$ being the largest dimension of the antenna and $\lambda$ the signal wavelength.
- The unit to be assessed. In most cases, this is the electric field E [V/m]. However, it is also possible to estimate SAR [W/kg], which is the rate of absorption of radiated energy by the human tissue per unit weight that depends on E; but also, the power density S [mW/cm or uW/cm], which is the amount of energy of the EMF exposition in a certain area.
- The topology of the environment where the exposure is to be measured (open, closed, with or without buildings or scatterers).
- The desired level of accuracy or complexity.

Table 6 below gives a comprehensive comparison of the key methods referenced in the above-mentioned standards.

### *E. SUMMARY OF THIS SECTION*

This section reviews and compares the existing methods for estimating EMF exposure from cellular technologies. There are two ways of doing this: either by **calculation** (simulation, software) or by **measurement** (hardware). The former generally involves equations that are a function of the power radiated by an antenna. Standardisation bodies, such as ITU, recommend the methods referenced in this paper. The latter involves measuring instruments, sometimes with a large software layer, which can be used directly around an antenna. These methods, referred to in this paper as "conventional", have been used for several years for assessing cellular installations before 5G, but they only seem to be suitable for non-active antennas.

From Table 7 we can see which topics have been included in the key standards on EMF exposure produced from the International Electrotechnical Commission since 2011. The concepts of power density and SAR calculations and the simulations schemes known as ray tracing and full wave have are presents in all documents. The simulation method known as Method of Moments and new mobile characteristics of 4G and 5G are considered since 2017, being mentioned starting

**TABLE 6.** Overview of exposure assessment methods (source: [25], [32]). E: Electric Field [V/m], S: Power Density [mW/cm], SAR: specific absorption rate [W/kg].

| Method | Field zone | Units | Environment | | | Accuracy | Complexity/data needed |
|---|---|---|---|---|---|---|---|
| | | | Outdoor | Indoor | Obstacles | | |
| Point source with isotropic antenna | Far-field | E, S | ✓ | ✓ | ✓ | Very low | Very low |
| Point source with radiation pattern | Far-field | E, S | ✓ | ✓ | ✓ | Low | Low |
| Synthetic | Far-field | E, S | ✓ | ✓ | ✓ | Medium | Medium |
| Ray tracing | Far-field | E, S | ✓ | | | High | Medium |
| Method of Moments (MoM) | Near-field | E | ✓ | ✓ | ✓ | Very high | Very high |
| Finite Difference Time Domain (FDTD) | Near-field | E, SAR | ✓ | | | High | High |
| Multiple-Region FDTD (MR-FDTD) | Near-field | SAR | | ✓ | ✓ | High | Very high |

**TABLE 7.** Comparison of IEC standards (I: included, NI: not included, NA: not applicable).

| Year | 2011 | 2017 | 2019 | 2022 |
|---|---|---|---|---|
| Name of document | IEC62232 | IEC-62232 Ed.2 | IEC-TR62669 | IEC-62232 Ed.3 |
| Type of document | Standard withdrawn | Standard | Technical report | Draft |
| Power density | I | I | I | I |
| SAR | I | I | I | I |
| Ray tracing | I | I | I | I |
| Full wave | I | I | I | I |
| Method of Moments | NI | I | I | I |
| FDTD | NI | I | I | NI |
| Finite element method | NI | I | I | NI |
| Overestimation analysis | I | I | I | NI |
| Temp. analysis metric | NI | NI | NI | NI |
| Max. pwr. considered | Nominal power | Max power (instead of nominal) | NA | NA |
| Uncertainty | I | I | I | I |
| WCDMA | I | I | I | I |
| LTE | NI | I | I | I |
| 5G analysis | NI | NI | I | I |
| Massive MIMO | NA | Spat. multiplexing | I | I |
| Beamforming | NA | NI | I | I |
| Beamsteering | NA | NI | I | I |
| MIMO | NA | I | I | I |

from the release IEC-62232 ed.2. The interested reader can refer to these documents to get more insights about the EMF assessment methods that are in place in a number of countries.

## V. RF-EMF EXPOSURE ASSESSMENT, PART 2: 5G-AAS METHODS

Conventional approaches to RF-EMF compliance assessment mainly consist of calculating a theoretical maximum power and assuming that it is emitted constantly and stably over a long period. This way of estimating EMF exposure was mostly sufficient before 5G, but it is not adequate today. As described in the section above, 5G NR comes with several differentiating factors compared to previous radio access technologies:

- **'Beam-centric design'** [33]: transmits energy precisely in the demanded direction rather than constantly sending it over a broad region,
- **Higher frequencies**,
- **Dynamic timing parameters**,
- **Flexible numerology**.

The conventional way of calculating the emission compliance level does not consider 5G's dynamic nature in space and time. Unlike conventional models, 5G antennas can emit signals in different directions depending on the application and user demand. ICNIRP recommends averaging the EMF values over six minutes. This averaging time is not realistic in 5G since this would mean allocating all the theoretical maximum transmit power to a single user for that period. Furthermore, even if it were realistic, the compliance boundaries would indeed be overestimated, or at least very conservative (i.e., when all the possible beams operate at maximum power simultaneously [29]). This way of calculating the emission compliance levels can increase the complexity of deployments or make some configurations unusable [34].

The creation of specific methodologies dedicated to 5G is still a problem under evaluation by the scientific and industrial communities. We describe below the most popular approaches referenced from the literature.

### A. COMPARATIVE ANALYSIS

A few approaches emerged in the literature – but none is standardised. Most of them involve a mixture of measurements and calculations (either by extrapolation or simulations).

A study conducted by [35] indicates the maximum transmitted power levels and maximum Equivalent Isotropically Radiated Power (EIRP) for AAS to be used in 5G complying with most RF-EMF exposure standards. The methodology involves testing different frequencies in the 10 to 60 GHz range for array antennas in 5G-and-beyond networks. Table 8 describes the maximum power that can be transmitted while complying with the exposure limits imposed by different entities: the US Federal Communications Commission (FCC), the ICNIRP and the Institute of Electrical and Electronics Engineers (IEEE). The authors compared these limits with power density simulations by considering several factors such as array topology, effects of frequency and beam steering range.

The authors conducted a survey of the simulation methodologies for a canonical monopole antenna. They employed the commercial electromagnetic solver FEKO [36] based on the Method of Moments and scenarios with antenna arrays directed towards human bodies.

To assess the maximum exposure, they determined the electric and magnetic fields in front of an antenna, from 0 to 0.5 m. Additionally, they defined a minimum sampling density of four samples on each wavelength. The authors chose an arbitrary set of array sizes to cover several applications. However, only a subset of them may be relevant for a particular application. The main finding of this study is that the maximum transmitted power is significantly below the user equipment power levels considered for existing 3G and 4G systems.

In [33], Thors et al. present a theoretical model to estimate the time-averaged realistic maximum power levels to assess RF-EMF exposure for 5G using Massive MIMO. The model applies conservative assumptions of a 5G-and-beyond network and employs a statistical approach to distribute the energy transmitted. A vital parameter of the model is the distribution of users within the cell. The authors found that the time-averaged realistic maximum power levels were significantly below the theoretical maximum (7% - 22%). for all user distribution scenarios. Thors et al. conclude that the results provide valuable input to the standardisation of RF-EMF exposure assessments in the vicinity of a radio base station.

Chiaravilio et al. consider in [7] the impact of exposure regulations on 5G network planning. The authors analyse the EMF exposure on two real-world case studies of already deployed mobile networks. They utilise the ray-tracing simulator proposed by [37] with the following input parameters:

- A Digital Elevation Model (DEM) that describes the scene.
- The vertex position and height of the buildings are contained in a vector file.
- The location, input power, radiation diagram, and pointing angles of the employed antennas.

This simulator applies electromagnetic models, which consider both reflection and diffraction, to describe the EMF levels exposed from each transmitter. Their findings suggest that the deployment of new 5G sites, particularly in urban areas, might be hindered by the EMF saturation effect. Additionally, they highlighted that strict regulations, limiting the installation of new BS sites, can affect the quality of services offered by service providers and ultimately the user's Quality of Service (QoS).

The authors of [38] conducted a case study in Italy to investigate the installation requirements and permission for 5G networks, where the regulation is more strict than in ICNIRP guidelines. Italy was the first country in the world to legislate on radiation protection, putting in place three main limits:

- Exposure limits, which are maximum 20 V/m for radio systems,
- Attention value, which is maximum 6 V/m for exposures prolonged over 4 hours,
- Quality value, which is maximum 6 V/m in intensively frequented areas.

Through their study, Persia et al. analysed the existing installation challenges, particularly the influence of the current regulation and EMF saturation areas. They conclude that the constraints imposed by the regulatory framework may pose a severe threat to the roll-out of 5G networks, as more and more areas (including rural ones) are already saturated with EMFs and therefore cannot accommodate new antennas.

The study in [7] provides recommendations on EMF-aware antenna configurations. It also uses a new EMF exposure index, "condensing in a single parameter multiple factors such as the temporal and the spatial variation of traffic" or the transmitted power. The article also includes a real-world case study from Italy that aims to identify the features for each antenna installed. The authors focused on several factors, including the antenna location, height, the azimuth, the downtilt, the gain and the frequency band.

Keller states in [39] that the current human exposure to the EMF transmitted by 5G NR base stations can be assesed using general assessment methods. However, [39] also claims that extrapolating to the theoretical maximum exposure is only possible under certain preconditions. The author enumerates two potential extrapolation methods: the frequency-selective method and the synchronisation signal demodulation-based method. For those options, the preconditions for the second seem more feasible in practice.

Aerts et al. introduced and tested in [40] a five-step assessment methodology in-situ for the exposure to RF-EMFs emitted by 5G NR base stations:

1) Identify the 5G NR channels with a spectrum overview.
2) Identify the frequency position, the channel bandwidth and the subcarrier spacing (SCS) of the synchronisation signal block (SSB), containing the 5G NR "always-on" signals.
3) Measure the electric field (E) strength per user of the SSB.
4) Measure the average exposure level.
5) Extrapolate the E strength per user to the theoretical maximum E level, in comparison to a fully occupied 5G NR channel.

Furthermore, the authors claim that they can add additional factors to the theoretical maximum exposure level to obtain the actual maximum exposure level:

- a spatial duty cycle factor (for spatial multiplexing of Massive MIMO),
- a temporal duty cycle factor,
- a TDD factor.

**TABLE 8.** General public/uncontrolled basic restrictions on power density and slim. The parentheses behind the power density limits indicate the applicable averaging area. The absence of averaging area implies spatial peak power density.

| | ICNIRP | FCC | IEEE | |
|---|---|---|---|---|
| f (GHz) | 10 - 300 | 6 - 100 | 3 - 30 | 30 - 100 |
| Slim ($W/m^2$) | 10 (20 $cm^2$)<br>200 (1 $cm^2$) | 10 (20 $cm^2$) | 10 (100$\lambda$)<br>$18.56 * f^{0.699}$ | 10 (100 $cm^2$)<br>200 |

**TABLE 9.** Ofcom power density level computation.

| Frequency range | Power density ($W/m^2$) |
|---|---|
| 400 to 2,000 MHz | $f/200$ |
| 2 to 300 GHz | 10 |

One of the study's limitations on [40] is that the assessed BS was not part of a commercial network and transmitted with a fixed beam. Moreover, while using just one UE allowed validating the proposed methodology in a well-controlled environment, other tests should be carried out in a live network to generalise the methodology. In addition, the authors were unable to perform tests with mmWaves, but they state that the procedure should remain valid for higher frequencies. Finally, the study focuses on measuring BS downlink exposure, leaving future work to analyse how UEs and uplink signals influence the measurements.

Another study [2] proposes a new approach for assessing EMF exposure utilising simulations and calculations. The process determines EMF distributions continuously without needing expensive on-site probing. However, the employed propagation model needs to consider buildings surrounding the BS. Hence, the method's accuracy heavily depends on the complexity of the location topology. Although it may provide an accurate measurement, the ray-tracing method of the scenario might be heavy to compute depending on the execution environment.

To verify that 5G base stations remained within the EMF emission limits set out in the guidelines from ICNIRP, Ofcom [41] conducted an experiment that included measurements at 22 UK sites. The authors employed a field strength analyser (i.e., Narda SRM-3006) with an isotropic probe to measure the EMF exposure level at selected test locations. Then they computed the power density reference levels as shown in Table 9. The measurements correspond to the frequency bands used for the base station transmissions and all other frequency bands between 420 MHz and 6 GHz.

### B. DISCUSSION: HOW CAN AI HELP WITH 5G EMF ASSESSMENT?

Machine Learning (ML) is a part of AI that helps computers get better at tasks by themselves, without being programmed. A computer program is said to learn from experience to perform some tasks if the program's performance on that task – measured by some metric – improves based on the provided experience. The literature usually divides machine learning algorithms into supervised, unsupervised and reinforcement learning. Many of these algorithms overlap with statistics, but ML sometimes finds relationships between data that do not have a statistical justification. Usually, the learning takes place by updating parameters to minimise or maximise a loss or cost function. The difference with traditional optimisation is that ML aims to generalise patterns to unseen data. To the best of our knowledge, no ML studies target EMF emission assessment for 5G, so the following recommendations are purely theoretical.

Supervised machine learning algorithms can identify patterns that relate features (measurable characteristics of the data, do not confuse with AAS features) to labels (a particular property of the data). The learning or training process occurs when the algorithms search for patterns based on examples for which the labels are known. The result is a model, an approximation of the underlying relationship between features and labels. During the testing step, the model assigns labels to samples that were not part of the training phase, and evaluation metrics compare these assignments or predictions to known labels. The purpose is to evaluate how well the model generalises to unseen cases. If each label is a real-valued number, a supervised machine-learning problem is known as a regression. In the context of EMF emission assessment, regressions can be valuable for predicting emission levels based on a collection of past feature-label pairs. The features could be, for example, AAS configuration parameters, building locations, weather conditions, time, and space coordinates, while the labels would be actual EMF emission measurements. The big issue with this approach is that, at the moment, a labelled EMF emission dataset does not exist for 5G (or if it does, it is not publicly available). Note that collecting such a dataset would be valuable both for academic and commercial purposes.

Taking just a few measurements is usually not enough since ML requires a considerable amount of data to produce valuable predictions. An ML model needs to learn from a more significant number of data points than the number of parameters it contains to avoid overfitting. A model is overfitting when it matches a particular set of data too closely or exactly and may therefore fail to generalise future observations reliably. It is equivalent to say that the model has a high variance because a slight change in the training dataset can cause a significant change in the resulting predictions. In other words, the model memorises some examples instead of understanding the big picture. We can avoid this issue in many ways, but every alternative involves acquiring more data or

**TABLE 10.** Comparative matrix of existing study on 5G exposure assessment methods.

| # | Goal | Factors / Parameters | Method / Case Study | Results / Findings | Limitations |
|---|---|---|---|---|---|
| [35] | Investigate max transmitted power levels and EIRP for exposure standards. | Array topology, beam steering range. | **Simulations**: Antenna arrays transmitting directly towards humans. | Max transmitted power significantly below considered UE 3G/4G power levels. | Theoretical approach, no comparison with real data. |
| [33] | Estimate time-averaged realistic max power levels for RF-EMF exposure assessment from 5G NR BSs. | System utilization, number of users, beam direction. | statistical models and different scenarios per user distribution. | Time-averaged realistic max power 7% - 22% below theoretical max. | Theoretical approach, no comparison with real data. |
| [7] | Planning 5G networks within the EMF exposure limits. | Digital elevation model. Buildings with vertex position and height and Antenna's location, radiation diagram and input power. | Ray-tracing [37] | Strict regulations lead to suboptimal planning impacting QoS. | Result accuracy significantly depends on the scene models' accuracy. |
| [34] | Investigate the impact of the restrictive approach on the future 5G networks roll-out. | Transmitted power over 24hs and antenna configuration. | Compare EMF around BSs (generating iso-level curves) for existing 2G/3G/4G technologies and adding 5G microcells and macrocells. | 5G development can be threatened by strict regulations. | Very simplistic approach. |
| [39] | Extrapolate theoretical EMF exposure for 5G. | Maximum field strength | Extrapolation of the frequency selective and SS demodulation (see citation). | Current EMF exposure transmitted by 5G NR BSs is assessable with broadband field strength meters | Extrapolation to the theoretical maximum exposure can be assessed only under certain conditions. |
| [40] | Assess in-situ exposure to RF-EMFs from 5G NR BSs. | SA mode, Centre Frequency, Span, Detector, Resolution Bandwidth, Measurement Time. | Common spectrum analyser and extrapolation | Same as [39] but with less extrapolation preconditions. | Tested outside a real network with only one UE. No mmWave analysis. No DL analysis. |
| [2] | Analyse issues and challenges related to EMF measurements in 5G technology. | Proposes no method for 5G. | Common spectrum analyser and extrapolation. | Propose statistical models as best candidates for 5G EMF estimation, but suggest more intensive testing in real networks. | Theoretical analysis and survey, no method proposed. |
| [41] | Measure and verify that 5G BSs remain within the EMF limits set out in the ICNIRP guidelines. | Location, frequency range, and bandwidth. | Field strength analyser (Narda SRM-3006) connected to an isotropic probe. | 5G is a small part of the measurements compared to 2G/3G/4G. | Measurements averaged over six-minute periods (might not be realistic for 5G). |
| [29] | Estimate possible maximum EMF exposure for 5G VS previous generations. | Centre frequency, bandwidth, and number of SS-Block per SS-Burst. | Laboratory-based work using N5172B EXG X-Series Vector Signal Generator and N9020A MXA Vector Signal Analyzer (Keysight). | Proposed extrapolation method is an effective tool for a correct evaluation of the instant maximum EMF level radiated by 5G sources. | Choosing the right pilot channel for extrapolation is hard. The method requires forcing the data link toward the measurement point. |
| [42] | Demystify the popular belief that narrow beams increase exposure levels radiated by 5G BSs. | 28 antenna parameters. | Simulator called 5G-PENCIL. | EMF increase from pencil beamforming is not supported by scientific evidence. | No pencil beam activation/deactivation over space and time. No tracking UE mobility over the territory. No mmWave testing. |

lowering the model complexity. However, if a model is not complex enough, it can underfit, producing biased predictions (systematic errors). A simple example of underfitting is trying to approximate a quadratic curve with a straight line. Choosing a suitable model complexity (the bias-variance trade-off) is just one of the tasks of an ML practitioner, so what we should worry about in the EMF assessment for 5G is how to solve the lack of data dilemma.

Since EMF emission data from previous generations is already available, a potential approach could involve employing previously trained 4G EMF emission prediction models as the foundation for predicting 5G EMF emissions (a method known as transfer learning). As discussed in previous sections, given the differences between 4G and 5G, we need to improve the EMF emission assessment for the new generation. Hence, older ML models would not give accurate predictions out of the box. However, one known transfer learning technique consists of using the learned parameters of the older model as part of the initialisation parameters of the new model (instead of the usual random initialisation). Another alternative is to use the prediction of the 4G model as a first guess for the 5G model. In this scenario, the 5G model can ask the researchers to confirm labels by measuring in an optimal order. The ML literature identifies this procedure as active learning, but the statistics field employs the term "optimal experimental design". Additionally, it supposes that the algorithm is involved in the antenna deployment phase. In that case, it can select the installation position that provides the most valuable scenarios to measure (i.e., unseen data points that would help us generalise faster).

Some organisations can already possess some labelled 5G emission data. However, in many cases, companies cannot share data for privacy reasons. In other cases, they consider that data a strategic advantage and would rather keep it to themselves. Nevertheless, organisations can benefit each other by using federated learning without explicitly sharing their data. The whole idea involves an iterative procedure that can be summarised as follows:

- **Initialisation**: an ML model (e.g., linear regression or neural network) is chosen and initialised (usually with random parameters), and participants wait for the first round.
- **Selection**: a fraction of participants are selected. The selected participants receive the global model whilst other users are put in hold for the next round.
- **Configuration**: the participants train based on the received model and local data.
- **Reporting**: each selected participant sends their local model. The next round starts with another selection phase presenting a global model resulting from the aggregation of all the participant models.
- **Termination**: the process terminates after meeting some predefined criterion (e.g., after reaching a given number of iterations or when the accuracy is high enough).

There are many aspects to be studied involving not only ML but also networking and security. For example, the whole process can be centralised or decentralised. In centralised federated learning, one server orchestrates the different steps and coordinates all the participants during the learning process. The server selects participants at the initialisation step and aggregating the received model at the reporting step. Since all participants send updates to the server device, this becomes a bottleneck. In the context of this 5G emission assessment, organisations participating in a federated learning process would have to choose a central server trusted by everyone. In the decentralised setting, the participants can coordinate to obtain the global model, preventing single point failures as there is no need of server orchestration. The network topology can make more difficult the learning process, but reducing training times might not be an issue for the 5G emission assessment context. Additional related topics that focus on the security aspects of federated learning are:

- **Homomorphic encryption**: a form of encryption that permits computations on encrypted data without first decrypting it. Federated learning algorithms can use it to aggregate encrypted models directly.
- **Differential privacy**: a technique that alters the data to hide information from individual samples but preserves the original data distribution. Participants can employ this tactic to ensure that others cannot reconstruct their local data from the shared models.
- **How to aggregate the models**: the most straightforward way is to average the parameters, but there are many other approaches to study.
- **Detecting malicious participants**: sometimes, a participant could sabotage the whole process by sending bad model updates on purpose. In other cases, a participant could not be aware that their local data does not reflect a meaningful distribution for the entire group.

There is no labelled data available in unsupervised learning, and the goal is to organise data and identify patterns or relationships. Possible uses of this technique could be grouping or clustering 5G antennas, which is not a trivial manual task given the numerous antenna features. Antennas in the same cluster are very similar, while antennas are as dissimilar as possible between different clusters. Clustering could help to identify emission categories or comparable deployment costs. Anomaly detection is another unsupervised learning technique that could find unusual setups for 5G antennas. Companies could determine that a 5G antenna would be too different from their previous deployments and requires additional analysis.

Finally, in reinforcement learning, one or more agents learns how to improve in a task by receiving rewards after taking actions inside an environment. For example, if there are simulations available to recreate 5G emissions, then reinforcement learning could aid companies in deciding how to cover territory with the least number of antennas following emission constraints (and indicate the best deployment order).

### *C. SUMMARY OF THIS SECTION*

This section explains why the conventional **methods used for previous generations are not compatible with 5G installations**, which come with antennas that are active in time and space. The main reason for this is that the result is generally overestimated, and given the higher density of antennas coming with 5G (and later on with 6G), this can easily lead to saturation of EMF levels at a base station. In other words, the deployment of 5G or the performance of current networks can be badly affected by this overestimation, and new methods need to be found, which are more realistic and take into account an antenna's dynamics. A review of the approaches proposed in the scientific literature is therefore conducted. However, at present, none of these approaches is standardised, and most of them rely on a combination of complex measurements and theoretical models - thus hindering adoption by regulatory bodies. Other possibilities, still poorly addressed in the literature and based on artificial intelligence (e.g., transfer learning), are then proposed.

## VI. TOWARDS EMF-AWARE NETWORK PLANNING, DESIGN, AND OPTIMISATION

Estimating EMF exposure is crucial and one of the many aspects to consider during 5G networks deployment, but yet most of existing optimisation engines for network planning do not or poorly consider it [42]. Just as the estimation of EMF exposure influences the design of the network, the optimised combination of resources respecting the regulatory limits also has an impact on the corresponding planning steps [43].

In this section, we address optimisation techniques suitable to network planning, design and optimisation considering EMF exposure factors.

### A. THE NEED FOR PLANNING AND OPTIMISATION

With 5G, the challenge of optimally planning the deployment of new antennas is paramount and can be immensely complex [44]. Connections have ten times the capacity of 4G, and the antennas planned for deployment can reach household scales [45]. Further down the line, 5G aims to be a more inclusive generation, offering virtualisation solutions and solutions to converge with unlicensed networks like Wi-Fi – thus increasing the complexity of the network [46]. Finally, the fibre network serving all these antennas and the costs involved (e.g., rental and energy) can be significant for the operator.

Implementing a 5G service implies setting up an adapted infrastructure and deploying dedicated base stations, called next-generation Node-B base stations (gNB). Selecting the type, characteristics, positioning and configuration of these antennas is known as network planning [47], which is an aspect that has always existed since the first mobile networks. This delicate task must consider all constraints that can occur in practice, such as the necessary coverage, intended applications, electromagnetic limits, and regulatory aspects (e.g., permitted or not permitted locations) [48]. Planning can quickly become a complex problem for operators due to their financial and commercial objectives and the need to maximise performance expectations [49].

Regulatory constraints can severely impact the deployment model, especially in countries with limits below those recommended by ICNIRP. These restrictions can narrow the number of deployed antennas or compromise antenna performance (e.g., reducing the output power) [50].

As seen in the previous section, EMF exposure estimation methods should include the temporal and spatial variations of 5G. However, regardless of regulatory limitations and estimation methods, 5G network deployment planning would benefit significantly from an optimisation approach. Optimisation techniques can minimise the system constraints while maximising performance depending on the application need (throughput, low latency, or QoS/massive connectivity) [29]. In this context, the link between AI and optimisation is crucial. AI can break down a model into simpler pieces and reduce possible solutions to find the optimum [51]. These techniques can also benefit from expert knowledge acquired via experimental campaigns and external actors (e.g., operators and regulatory bodies).

In addition to the regulatory considerations recognised in this paper, 5G comes with new technical elements that have a considerable impact on network deployment:

- The number of devices and the volume of data will explode,
- Network capacity will be revised accordingly, increasing the number of antennas, and using other frequency bands,
- The development of a true end-to-end network, or using massive virtualisation technologies, requires a robust server infrastructure.

In other words, finding the best configuration for an antenna requires considering many parameters, as highlighted in Section IV-A. This consideration increasingly justifies the need for optimisation systems to achieve suitable solutions while existing the technical and regulatory constraints.

### B. REQUIREMENTS, PARAMETERS, CONSTRAINTS, VARIABLES, AND PROBLEM DEFINITION

The main purpose of a mobile wireless network is to provide users with a guaranteed quality of service (QoS) and reliable coverage across a certain region, considering the increase demand of the users and without compromising the established regulations on limiting EMF exposure [52]. Indeed there is no single solution to a particular problem in real-life situations: it all depends on the perspective and the various objectives required to solve it. However, solving such a problem can be complex as these objectives can sometimes be contradictory [53]. Referring to the facts mentioned above, multi-objective techniques should come into play by using optimisation algorithms to calculate a set of possible solutions.

Decision-making is the process of selecting the most appropriate and feasible option from a set of options, targeting at least one goal, and considering at least one criterion. Accordingly, the decision-making process includes decision-maker(s), option(s), criterion/criteria, environmental impacts, the priorities of the decision-maker and the results of the decision. The process may end with a ranking or classification of the available options made by the decision-maker [54]. At this stage, multi-criteria and multi-objective decision-making methods emerge to make the right decision. In addition to multi-Objective decision methods, multi-criteria decision-ranking methods help decision-makers to make the most appropriate decision using numeric and categorical data [55] - which might be of specific interest for network planning.

There are many factors, indicators, performance measurements and techniques related to optimisation in EMF-aware network planning and 5G topics. The aim of the current section is to systematically reference the elaborated research question, defined constraints, predefined parameters, variables, and the approach taken by the authors identified from the literature.

However, before targeting exposure-related topics, planning and optimisation for 5G radio access are worth considering. This way, in addition to the objective of 5G exposure optimisation, we can see other objectives to be considered while planning for the deployment of a BS.

The work of Pérez-Romero et al. [56] considers an AI concept that covers various optimisation techniques and targets radio access network planning in 5G systems with analysing Self-Organising Network (SON) functionalities.

The authors proposed a data mining framework to process data and extract insights to help decision-making for 5G SON functionalities. They highlighted the applicability of their analysis framework to 5G SON functions by taking into account objectives such as self-planning, self-optimisation and self-healing. They also identified the following research directions:

1) Coverage and capacity optimisation,
2) Mobility robustness optimisation,
3) Mobility load balancing,
4) Optimisation of admission control / congestion.

Plets et al. [57] considered the coverage of Wi-Fi Access Points (APs) and LTE femtocells to calculate and optimise the coverage of indoor wireless networks. As a solution for their optimisation model, they proposed an heuristic algorithm that successfully made EMF levels 3 to 6 times less important than previous approaches targeting homogeneous EMF levels in a given building. They used the same approach, focusing on the outdoor 5G network access infrastructure planning to better align with future generation networks.

Chiaraviglio et al. [7] analysed the severity of EMF limits using various sets of evidence. The site selection problem for 5G BSs under EMF limits is one of the main drivers for their 5G network planning approach. The paper performed a comprehensive related work analysis of 5G exposure limits and their impacts on the planning process of a 5G network. The authors explored two realistic case studies to reach saturation of the EMF level. They elaborated a direct correlation between quality of service and the strictness of regulative limits. This work considered the following constraints:

1) EMF regulation constraints:
    a) EMF exposure limit (in V/m),
    b) Distance between a BS placement and a sensitive location (i.e., schools or hospitals),
    c) Height of the antenna.
2) Presence of an EMF saturation zone,
3) Maximum demand and minimum/maximum support constraints,
4) Maximum input power (in W),
5) Reference Signal Received Power (RSRP).

### C. MATHEMATICAL SOLUTION APPROACHES

This section describes the solution approaches using some comprehensive and essential works to guide the reader into the nature of the problem and the related solution.

In the following lines we summarise the related literature's problem solution challenges, achievements and future directions. A future work would be to use these approaches to propose specific solutions for 5G network planning under EMF constraints.

In [58] a metaheuristic for joint optimal power and scheduling assignment in digital video broadcasting networks is proposed, using a binary linear programming mathematical model. In this proposal, a genetic algorithm is used to obtain a higher user coverage using different power and scheduling configurations. The authors propose for the future a better solution with a branch-and-cut approach inserted into the current genetic algorithm. A network design with optimal performance considering exposure, space management and overall costs is proposed in [59]. A multi-objective optimisation model is applied using the "Hybrid Optimisation of Multiple Energy Resources" (HOMER) software. The authors develop cost-effective and environmentally friendly powering network schemes. In the future they propose to consider policy makers and telecommunication regulators. In [60] a user-centric association decision system for green communications is proposed where a Multi-Integer Linear Programming (MILP) and particle swarm optimisation (PSO) algorithms are used. Simulation results are obtained for the capacity utilisation of the overall system compared to the traditional uncontrolled system. An Optimal Filter Length and Zero Padding Length Design for the Universal Filtered Multi-Carrier (UFMC) System is proposed in [61]. An optimisation problem is formulated to minimise the variance of instantaneous power in [62]. The mathematical model used is a quadratic objective function which is evaluated using a majorisation–minimisation algorithm. As result the detection reliability and spectral efficiency for practical 5G cases is improved. In [63], a trade-off between the spectral efficiency (SE) and energy efficiency (EE) in cellular cognitive radio networks (CCRN) is proposed. The mathematical model used is a multi-objective optimisation model, which is evaluated through a branch and exchange approach. The analysis demonstrates that the relationship between SE and EE in CCRNs is not opposite, and that the optimal trade-off between SE and EE can therefore be achieved. To optimise the receiver-centric framework in [64], the authors proposed to use a Network-Graph Optimisation model using a receiver-centric network optimisation framework. This framework achieves higher spectrum efficiency gains. Additionally, they proposed as future research the use of non-fixed channel bandwidths and demand-based resource allocations via algorithms. In [65], an optimisation approach for quantum-efficiency tuning is proposed using Goal Programming as a mathematical model and Simulated Annealing as algorithm. The authors obtained the first significant emission control of pbs quantum dots at telecommunication wavelength. To design a framework for traffic-aware energy optimisation in [66], a Multi Objective Programming model is proposed and treated using a stochastic game theory algorithm. This algorithm achieves almost 25% daily energy savings and 35% increased energy efficiency. In [67], a filter optimisation method for suppressing out-of-sub band (OOSB) emissions in UFMC systems is proposed. Minimising energy in wireless multicast networks is proposed in [68] using data envelopment analysis (DEA) with input-oriented variable return. In [69], the optimisation of optical features for narrow-band emission in the wavelength range is showed. Finally, in [70] the optimisation of integrated circuits placement for reduction of electric field inside equipment is implemented with parallel programming and Monte Carlo simulations.

### D. EMF MITIGATION TECHNIQUES

Once the assessment of EMF exposure in 5G communications is completed, the next step is, whenever is possible, to reduce them while maximising the performances of the network. In order to do that, we could consider the variables that affect EMF exposure and evaluate how we can optimise the connectivity to mitigate its effects. However, first, we revise the state-of-the-art on this topic, and we then propose some extensions to these optimisations as a starting point for future work.

Since EMF exposure is strictly related to received power, most efforts to mitigate its effects are to reduce the received power or sparse it through a larger area, so that EMF exposure to a single user is minimised. Towards this direction, the main published works related to the mitigation of EMF effects are the following:

- Open loop power control: It can adjust the received power usually used to balance the edge users in a cell radius, but it can also be used to reduce the power once the EMF levels are over the exposure limits [71]. An alternative is proposed in [71], where the authors include an Exposure Index-based Power Control Algorithm which maximises the power control for a set of users to maintain the threshold.
- Downlink optimisation through PD detection: In [72], authors develop an algorithm to evaluate the PD level (and therefore the SAR exposure) and disables the Base station (BS) once the threshold is achieved.
- Use of RIS (Reconfigurable Intelligent Surfaces) as a passive Relay: To support a high data rate, mmWave communications are essential. However, the Line-Of-Sight (LoS) path can be blocked, leading to a considerable decrease in the received signal. Therefore, the UE must increase its transmission power and it consequently results as an increase to the EMF exposure as well. A solution to this problem is to consider a BS acting as a relay to split the link: a first channel BS-relay and a second one relay-UE. RISs are somewhat inactive components since they work as reflectors without RF chains, thus lowering energy use. They can reduce EMF exposure, while enhancing the wireless channel. They aim the signal beam at the receiving device to create a direct LoS link for the UE [73]. Especially when the direct LoS paths between the devices and BS are blocked.

### E. OPTIMISATION PROPOSALS

In addition to the usual KPIs optimisation based on the connectivity performance, such as the achievable rate or coverage probability, or even more related 5G KPI's such as spectral efficiency or low latency, here we focus on the parameters that affect the EMF emissions. We leave for future work the exploration of the following techniques:

- Nowadays, ultra-dense scenarios are considered for communications. This fact implies that the UE will be able to select a full range of available resources to attempt a connection. Therefore, we would like to propose a resource-allocation algorithm that minimises the power density. Furthermore, resource-allocation algorithms have been used more frequently since the densification of the scenarios. Therefore, we suggest applying them for EMF mitigation.
- Enhancement of uplink communications: In beyond-5G and 6G mobile generations, users are expected to have the same data rate in UL and DL communications. A balanced link is required in applications involving D2D communications or IoT communications. Therefore, a similar optimisation of the EMF exposures in the UL link could be a potential line of research. Similarly, since transmitting power will increase to balance UL-DL links, the EMF exposure will also increase in the UL link (and consequently the SAR). Therefore, mitigation EMF techniques on the UL link will become necessary.
- Taking advantage of the proposal for using RIS to mitigate the effects of the Non-Light-Of-Sight (nLOS) and therefore avoid increasing the transmit power, we propose to explore the use of those surfaces to reduce the parameters shown throughout this paper, such as SAR.
- Rate-Splitting Multiple Access (RSMA) corresponds to a multiple access technique for downlink using multiple antenna wireless networks. It uses Rate-Splitting (RS) at the transmitter and at the receiver Successive Interference Cancellation (SIC). Relying on this would mean that less transmit power could be used to achieve the same performance.

### F. SUMMARY OF THIS SECTION

In this section, we went one step further than estimating EMF exposure and introduce issues related to **network planning** using techniques that combine **optimisation and artificial intelligence**. **Multi-objective optimisation techniques** are valuable for proposing solutions to a network deployment problem with multiple and sometimes conflicting objectives. For example, what is the ideal positioning and configuration of a set of antennas on a given territory, considering the EMFs limits in application and the performance and service level required by the operator? This type of problem can sometimes be complex, and the combined use of artificial intelligence can reduce its complexity, by choosing only the most plausible solutions.

This section attempted to review some of the most popular approaches in the literature where it opened up some exciting possibilities for future work. For example, there is a general need to develop solutions that adapt easily and quickly to a given situation to let operators simulate multiple configurations on the fly. This requirement for adaptation is significant because the real-time and dynamic nature of 5G

**TABLE 11.** **Scientific trends for the next 5-10 years.**

| Category | Topic | In this survey |
|---|---|---|
| **Energy** | Network efficiency improvement. | |
| | Dynamic/adaptive equipment and architectures (i.e., adjust power in real time). | |
| | Network-wide energy awareness (e.g., telemetry data acquisition, energy data analytics). | |
| | End-to-end network economic models. | |
| **Security** | Proactive security and privacy for 5G-IoT (ensure a reactive system by design; ability to predict security-privacy attacks while considering the 5G environment; privacy-aware solutions). | |
| **Massive MIMO** | AI and ML in Massive MIMO | ✓ |
| **Deployment** | Public acceptance. | |
| | Regulatory framework. | ✓ |
| | Technical barriers (e.g., security, energy). | |
| **Connecting the unconnected** | Cost-optimised network architectures. | ✓ |
| | Cost-effective solutions for local coverage. | ✓ |
| | Power and energy conservation. | |
| **AI/ML** | User equipment profiling. | |
| | AI-driven wireless network analytics. | ✓ |
| | Reliable connectivity, low latency, and high bandwidth services driven by AI/ML analytics. | ✓ |
| **Systems optimisation** | End-to-end automatic network management and control. | ✓ |
| | Self-optimizing techniques for autonomous/autonomic system behaviours. | |
| | Distribution and federation of intelligence across disparate contributing entities. | |
| | Application and context-specific performance optimisation. | ✓ |

antennas forces the study of many possible scenarios. Studying this dynamic nature is also valid after the deployment of the antennas, with the implementation of optimisation techniques.

## VII. CONCLUSION AND FUTURE WORK

Recent advances in cellular communications enable significant improvements in throughput, latency, quality of service and connectivity capabilities - opening the door to new applications and business cases. However, this evolution is not trivial and requires significant changes in the network deployment strategies, where EMF exposure becomes a key factor - which will probably become even more important with future generations (Advanced 5G, 6G).

In this survey, we have presented a comprehensive review of the existing literature on **EMF-aware network planning and design**, which includes a description of: (a) the fundamentals of cellular communications, (b) the existing regulatory framework, (c) non-AAS/5G exposure assessment methods, (d) AAS/5G assessment methods, and (e) AI and optimisation approaches for compliance assessment and better decision-making on deployment.

As a result, the main conclusions and takeaways raised in this paper are the following:

1) The **regulatory framework** has been in place for several years but now needs to address the emergence of new technologies affecting the way exposure assessments were performed with previous generations. This adaptation is made through measurement campaigns and in a very cautious way. It will need to be revised further with the arrival of the new frequency bands above 6 GHz (i.e., mmWaves).
2) The **methods used to assess RF-EMF exposure**, which have been standardised and in use for several years, is no longer valid for 5G, which offers antennas that are dynamic in time and space. These methods generally lead to an overestimation, which could potentially force operators to reduce the transmitting power of their antennas and thus the network and application performances. **New methods, which consider the characteristics of active antennas**, have been proposed for some years already, but they all have some limitations and are not yet fully standardised in all countries at the time of writing this study (i.e., 2022). Moreover, there is still a way to go to derive more realistic estimates.
3) Estimating the EMF level of a specific network configuration is only the first part of the problem. The other part is to take into account all regulatory constraints and desired deployment parameters (e.g., performance, users to be covered) to best **plan and design the deployment of a 5G network**. This is where **optimisation-based approaches** make sense as they allow to find or at least approach the optimal deployment parameters. The parallel use of artificial intelligence techniques is also essential since this allows the optimisation problem(s) to be limited, thus increasing efficiency. On this side, there are still many possibilities to be explored - in particular by proposing integrated approaches with real-time usability for the operators.

There are many opportunities for future work on this topic. Table 11 summarises the main research areas covered by the related work on EMF-aware mobile network planning and the areas that could benefit from this literature. Amongst these, we can, for example, find topics related to energy management, which would still involve aspects of optimisation and network planning but obviously with different parameters and issues.

In addition to these high-level directions, and following the literature review presented in this paper, the following pertinent future directions could involve:

1) Proposing a **multi-stakeholder decision-system**, so that regulators, telco operators and the various stakeholders of this sector can collaboratively decide about the future deployment plans.
2) Proposing and benchmarking **new exposure assessment methods made for 5G and beyond 5G networks**, by going further that what has been described in this paper, and which would consider the specific characteristics of the targeted deployments, for example, in Luxembourg. A potential approach could be to use artificial intelligence and transfer learning to approximate the most reliable emission estimate based on previous measurements.
3) Proposing new and more **efficient, flexible optimisation methods for EMF-aware network planning and design** (e.g., by considering a tolerance level on the deployment parameters).
4) **Optimisation and artificial intelligence techniques** are key to the topics addressed in this paper. They may be applied at different levels and can have a local (i.e., at the antenna level) or a global impact (i.e., entire network). The study of these different levels, and the implementation of advanced data science techniques to serve the field of EMF-aware network planning, is an exciting direction for future work - as is the extensive use of simulation and emulation.

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## REFERENCES

[1] A. Elzanaty, L. Chiaraviglio, and M.-S. Alouini, “5G and EMF exposure: Misinformation, open questions, and potential solutions,” *Frontiers Commun. Netw.*, vol. 2, Apr. 2021, Art. no. 635716.

[2] R. Pawlak, P. Krawiec, and J. Zurek, “On measuring electromagnetic fields in 5G technology,” *IEEE Access*, vol. 7, pp. 29826–29835, 2019.

[3] H. M. Madjar, “Human radio frequency exposure limits: An update of reference levels in Europe, USA, Canada, China, Japan and Korea,” in *Proc. Int. Symp. Electromagn. Compat.-EMC Eur.*, Sep. 2016, pp. 467–473.

[4] A. Ahlbom, U. Bergqvist, J. Bernhardt, J. Cesarini, M. Grandolfo, M. Hietanen, A. Mckinlay, M. Repacholi, D. H. Sliney, and J. A. Stolwijk, “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),” *Health Phys.*, vol. 74, no. 4, pp. 494–521, 1998.

[5] K. Campbell, J. Diffley, B. Flanagan, B. Morelli, B. O’Neil, and F. Sideco, “The 5G economy: How 5G technology will contribute to the global economy,” *IHS Econ. IHS Technol.*, vol. 4, p. 16, Jan. 2017.

[6] International Telecommunication Union. (2017) *Electromagnetic Field Level and 5G Roll-Out*. [Online]. Available: https://www.itu.int/en/ITU-D/Regional-Presence/Europe/Documents/Events/2017/EMF/ExpertMeetingReportFinal.pdf

[7] L. Chiaraviglio, A. S. Cacciapuoti, G. D. Martino, M. Fiore, M. Montesano, D. Trucchi, and N. B. Melazzi, “Planning 5G networks under EMF constraints: State of the art and vision,” *IEEE Access*, vol. 6, pp. 51021–51037, 2018.

[8] S. Sagar, S. Dongus, A. Schoeni, K. Roser, M. Eeftens, B. Struchen, M. Foerster, N. Meier, S. Adem, and M. Röösli, “Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: A systematic literature review,” *J. Exposure Sci. Environ. Epidemiol.*, vol. 28, no. 2, pp. 147–160, Mar. 2018.

[9] G. Pujolle, “Faut-il avoir peur de la 5G?” Larousse, Paris, France, Tech. Rep., 2020. [Online]. Available: https://www.editions-larousse.fr/livre/faut-il-avoir-peur-de-la-5g-9782035996541

[10] A. A. Zaidi, R. Baldemair, M. Andersson, S. Faxér, V. Molés-Cases, and Z. Wang, “Designing for the future: The 5G NR physical layer,” *Ericsson Technol. Rev.*, vol. 7, pp. 1–13, Jun. 2017.

[11] E. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*. Cambridge, MA, USA: Academic Press, 2020.

[12] *International Network Generations Roadmap: Executive Summary (First Edition)*. Accessed: May 5, 2021. [Online]. Available: https://futurenetworks.ieee.org/images/files/images/roadmap/INGR_ExecSumm_Ed1.pdf

[13] Belgian Institute for Postal Services and Telecommunications. (2018). *Study of 12, September 2018 on the Impact of the Radiation Standards in Brussels on the Deployment of Mobile Networks*. [Online]. Available: https://www.bipt.be/operators/publication/study-of-12-september-2018-on-the-impact-of-the-radiation-standards-in-brussels-on-the-deployment-of-mobile-networks

[14] J. Karpowicz, M. Hietanen, and K. Gryz, “EU directive, ICNIRP guidelines and Polish legislation on electromagnetic fields,” *Int. J. Occupational Saf. Ergonom.*, vol. 12, no. 2, pp. 125–136, Jan. 2006.

[15] World Health Organization. *Electromagnetic Fields*. Accessed: May 5, 2021. [Online]. Available: https://www.who.int/data/gho/data/themes/topics/topic-details/GHO/electromagnetic-fields

[16] R. Stam, “Comparison of international policies on electromagnetic fields (power frequency and radiofrequency fields),” Nat. Inst. Public Health Environ., RIVM, Bilthoven, The Netherlands, Tech. Rep., 2018. [Online]. Available: https://rivm.openrepository.com/bitstream/handle/10029/623629/2018998.pdf?sequence=1

[17] *European Union Law*, document 52000dc0001, 2000. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52000DC0001

[18] Journal officiel du Grand-Duché de Luxembourg. (1999). *Loi du 10 Juin 1999 Relative Aux Établissements Classés*. [Online]. Available: http://legilux.public.lu/eli/etat/leg/loi/1999/06/10/n5/jo

[19] Journal officiel du Grand-Duché de Luxembourg. (2012). *Règlement Grand-Ducal Du 10 Mai 2012 Portant Nouvelles Nomenclature Et Classification Des Établissements Classés Et Modifiant*. [Online]. Available: https://legilux.public.lu/eli/etat/leg/rgd/2012/05/10/n2/jo

[20] Inspection Du Travail Et Des Mines—Luxembourg. (2014). *ITM-SST 1105.1: Conditions d’Exploitation Pour Les Émetteurs D’Ondes Électromagnétiques á Haute Fréquence*. [Online]. Available: https://itm.public.lu/dam-assets/fr/securite-sante/conditions-types/itm-cl-1100-2000/ITM-SST-1105-1.pdf

[21] International Electrotechnical Commission. *Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*, Standard IEC 62232:2017, 2017.

[22] P. Pauli and D. Moldan, “Schirmung elektromagnetischer wellen im persönlichen umfeld,” Bayerisches Landesamt für Umwelt, Germany, Tech. Rep., 2008.

[23] *Méthode de Mesure Des Rayonnements Électromagnétiques Pour la Reception et le Contrôle d’emetteurs d’ondes Au Grand-Duché de Luxembourg*, Institut Scientifique de Service Public, Liege, Belgium, 2009.

[24] *The National Geoportal of the Grand-Duchy of Luxembourg*. Accessed: May 5, 2021. [Online]. Available: https://www.geoportail.lu/fr/

[25] International Telecommunication Union. (Dec. 2020). *K.91: Guidance for Assessment, Evaluation and Monitoring of Human Exposure to Radio Frequency Electromagnetic Fields*. [Online]. Available: https://www.itu.int/rec/T-REC-K.91-202012-I/en

[26] International Commission on Non-Ionizing Radiation Protection, “Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz),” *Health Phys.*, vol. 118, no. 5, pp. 483–524, May 2020.

[27] Global System for Mobile Communications. *Explanation of Calculation Basis*. Accessed: May 5, 2021. [Online]. Available: https://www.gsma.com/iot/wp-content/uploads/field_simulation/erlaeuterungen.html

[28] G. Vermeeren, A. Thielens, S. Aerts, W. Joseph, L. Martens, C. Oliveira, M. Mackowiak, L. Correia, M. Pejanovic-Djurisic, and Z. Veljovic, "D2.1 current metrics for EMF exposure evaluation," LEXNET Project, Deliverable D2.1 Eur. Project (LEXNET), Tech. Rep. D2.1, Apr. 2013. [Online]. Available: https://cordis.europa.eu/docs/projects/cnect/3/318273/080/deliverables/001-D21Currentexposuremetricsv40Ares20142440252.pdf

[29] D. Franci, S. Coltellacci, E. Grillo, S. Pavoncello, T. Aureli, R. Cintoli, and M. D. Migliore, "Experimental procedure for fifth generation (5G) electromagnetic field (EMF) measurement and maximum power extrapolation for human exposure assessment," *Environments*, vol. 7, no. 3, p. 22, Mar. 2020.

[30] European Committee for Electrotechnical Standardization, *Basic Standard for the In-Situ Measurement of Electromagnetic Field Strength Related to Human Exposure in the Vicinity of Base Stations*, CENELEC EN, Standard 50492, 2008.

[31] International Electrotechnical Commission, *Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*, Standard IEC TR, 62669, 2019.

[32] H. El Abdellaouy, "Optimization of routing mechanisms for green home network," Ph.D. Theses, IRISA Lab., Dept. Networks, Telecommun. Services, Télécom Bretagne, Univ. de Rennes 1, Rennes, France, Jan. 2015. [Online]. Available: https://hal.archives-ouvertes.fr/tel-01212832

[33] B. Thors, A. Furuskär, D. Colombi, and C. Törnevik, "Time-averaged realistic maximum power levels for the assessment of radio frequency exposure for 5G radio base stations using massive MIMO," *IEEE Access*, vol. 5, pp. 19711–19719, 2017.

[34] S. Persia, C. Carciofi, S. D'Elia, and R. Suman, "EMF evaluations for future networks based on massive MIMO," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1197–1202.

[35] B. Thors, D. Colombi, Z. Ying, T. Bolin, and C. Törnevik, "Exposure to RF EMF from array antennas in 5G mobile communication equipment," *IEEE Access*, vol. 4, pp. 7469–7478, 2016.

[36] Altair. *Simulation for Connectivity, Compatibility, and Radar*. Accessed: May 5, 2021. [Online]. Available: https://www.altair.com/feko/

[37] J.-H. Lee, J.-S. Choi, and S.-C. Kim, "Cell coverage analysis of 28 GHz millimeter wave in urban microcell environment using 3-D ray tracing," *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1479–1487, Mar. 2018.

[38] S. Persia, C. Carciofi, M. Barbiroli, C. Volta, D. Bontempelli, and G. Anania, "Radio frequency electromagnetic field exposure assessment for future 5G networks," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1203–1207.

[39] H. Keller, "On the assessment of human exposure to electromagnetic fields transmitted by 5G NR base stations," *Health Phys.*, vol. 117, no. 5, pp. 541–545, 2019.

[40] S. Aerts, L. Verloock, M. Van Den Bossche, D. Colombi, L. Martens, C. Törnevik, and W. Joseph, "In-situ measurement methodology for the assessment of 5G NR massive MIMO base station exposure at sub-6 GHz frequencies," *IEEE Access*, vol. 7, pp. 184658–184667, 2019.

[41] OFCOM. (2020). *Electromagnetic Field (EMF) Measurements Near 5G Mobile Phone Base Stations*. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0015/190005/emf-test-summary.pdf

[42] S. Bartoletti, L. Chiaraviglio, S. Fortes, T. E. Kennouche, G. Solmaz, G. Bernini, D. Giustiniano, J. Widmer, R. Barco, G. Siracusano, A. Conti, and N. B. Melazzi, "Location-based analytics in 5G and beyond," *IEEE Commun. Mag.*, vol. 59, no. 7, pp. 38–43, Jul. 2021.

[43] H. B. A. Sidi and Z. Altman, "Small cells' deployment strategy and self-optimization for EMF exposure reduction in HetNets," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7184–7194, Sep. 2016.

[44] R. Zi, X. Ge, J. Thompson, C.-X. Wang, H. Wang, and T. Han, "Energy efficiency optimization of 5G radio frequency chain systems," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 758–771, Apr. 2016.

[45] S. Chen, F. Qin, B. Hu, X. Li, Z. Chen, and J. Liu, *User-Centric Ultra-Dense Networks for 5G*. Berlin, Germany: Springer, 2018, pp. 1–3.

[46] A. Al-Dulaimi, S. Al-Rubaye, Q. Ni, and E. Sousa, "5G communications race: Pursuit of more capacity triggers LTE in unlicensed band," *IEEE Veh. Technol. Mag.*, vol. 10, no. 1, pp. 43–51, Mar. 2015.

[47] A. R. Mishra, *Fundamentals of Network Planning and Optimisation 2G/3G/4G: Evolution to 5G*. Hoboken, NJ, USA: Wiley, 2018.

[48] H. W. Ott, *Electromagnetic Compatibility Engineering*. Hoboken, NJ, USA: Wiley, 2011.

[49] P. A. Sarvari and F. Calisir, "Evaluating airline network robustness using relative total cost indices," in *Industrial Engineering in the Industry 4.0 Era*. Berlin, Germany: Springer, 2018, pp. 47–61.

[50] L. Chiaraviglio, A. Elzanaty, and M.-S. Alouini, "Health risks associated with 5G exposure: A view from the communications engineering perspective," 2020, *arXiv:2006.00944*.

[51] S. Bottcher, B. Doerr, and F. Neumann, "Optimal fixed and adaptive mutation rates for the leadingones problem," in *Proc. Int. Conf. Parallel Problem Solving Nature*. Cham, Switzerland: Springer, 2010, pp. 1–10.

[52] S. Wang and C. Ran, "Rethinking cellular network planning and optimization," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 118–125, Apr. 2016.

[53] A. Konak, D. W. Coit, and A. E. Smith, "Multi-objective optimization using genetic algorithms: A tutorial," *Rel. Eng. Syst. Saf.*, vol. 91, no. 9, pp. 992–1007, Sep. 2006.

[54] A. Latuszynska, "Multiple-criteria decision analysis using topsis method for interval data in research into the level of information society development," *Folia Oeconomica Stetinensia*, vol. 13, no. 2, pp. 63–76, Jul. 2014.

[55] Y. Zhong, H. Wang, and H. Lv, "A cognitive wireless networks access selection algorithm based on MADM," *Ad Hoc Netw.*, vol. 109, Dec. 2020, Art. no. 102286.

[56] J. Pérez-Romero, O. Sallent, R. Ferrus, and R. Agustí, "Knowledge-based 5G radio access network planning and optimization," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Sep. 2016, pp. 359–365.

[57] D. Plets, W. Joseph, K. Vanhecke, and L. Martens, "Exposure optimization in indoor wireless networks by heuristic network planning," *Prog. Electromagn. Res.*, vol. 139, pp. 445–478, 2013.

[58] F. D'Andreagiovanni, H. Lakhlef, and A. Nardin, "A matheuristic for joint optimal power and scheduling assignment in DVB-T2 networks," *Algorithms*, vol. 13, no. 1, p. 27, Jan. 2020.

[59] J. S. Ojo, P. A. Owolawi, and A. M. Atoye, "Designing a green power delivery system for base transceiver stations in southwestern Nigeria," *SAIEE Afr. Res. J.*, vol. 110, no. 1, pp. 19–25, Mar. 2019.

[60] A. Tahat, A. Mohammad, Q. Abu-Khlaif, L. Qatarneh, Z. Abu-Shamma, and O. Saraereh, "A semi-automated user-centric decision system for green communications incorporating the particle swarm optimization algorithm," in *Proc. Int. Symp. Netw., Comput. Commun. (ISNCC)*, Jun. 2019, pp. 1–6.

[61] L. Zhang, A. Ijaz, P. Xiao, K. Wang, D. Qiao, and M. A. Imran, "Optimal filter length and zero padding length design for universal filtered multi-carrier (UFMC) system," *IEEE Access*, vol. 7, pp. 21687–21701, 2019.

[62] Y. Huang, R. Yang, and B. Su, "Reducing cubic metric of circularly pulse-shaped OFDM signals through constellation shaping optimization with performance constraints," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–6.

[63] P. S. Yawada and M. T. Dong, "Tradeoff analysis between spectral and energy efficiency based on sub-channel activity index in wireless cognitive radio networks," *Information*, vol. 9, no. 12, p. 323, Dec. 2018.

[64] A. V. Padaki, R. Tandon, and J. H. Reed, "Efficient spectrum access and co-existence with receiver nonlinearity: Frameworks and algorithms," *IEEE Trans. Wireless Commun.*, vol. 17, no. 10, pp. 6404–6418, Oct. 2018.

[65] M. D. Birowosuto, M. Takiguchi, A. Olivier, L. Y. Tobing, E. Kuramochi, A. Yokoo, W. Hong, and M. Notomi, "Temperature-dependent spontaneous emission of PbS quantum dots inside photonic nanostructures at telecommunication wavelength," *Opt. Commun.*, vol. 383, pp. 555–560, Jan. 2017.

[66] N. Saxena, A. Roy, and H. Kim, "Traffic-aware cloud RAN: A key for green 5G networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 1010–1021, Apr. 2016.

[67] M.-F. Tang and B. Su, "Filter optimization of low out-of-subband emission for universal-filtered multicarrier systems," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, May 2016, pp. 468–473.

[68] A. A. Ajibesin, N. Ventura, A. Murgu, and H. A. Chan, "Data envelopment analysis with slacks model for energy efficient multicast over coded packet wireless networks," *IET Sci., Meas. Technol.*, vol. 8, no. 6, pp. 408–419, Nov. 2014.

[69] A. Winden, M. Mikulics, D. Grützmacher, and H. Hardtdegen, "Vertically integrated (Ga, In)N nanostructures for future single photon emitters operating in the telecommunication wavelength range," *Nanotechnology*, vol. 24, no. 40, Oct. 2013, Art. no. 405302.

[70] S. K. Goudos, Z. D. Zaharis, P. I. Lazaridis, and P. B. Gallion, "Optimization of integrated circuits placement for electric field reduction inside telecommunications equipment using Monte Carlo simulation and parallel recombinative simulated annealing," *Microw. Opt. Technol. Lett.*, vol. 49, no. 12, pp. 3049–3055, 2007.

[71] A. T. Ajibare, D. Ramotsoela, L. A. Akinyemi, and S. O. Oladejo, "RF EMF radiation exposure assessment of 5G networks: Analysis, computation and mitigation methods," in *Proc. IEEE AFRICON*, Sep. 2021, pp. 1–6.

[72] I. Nasim and S. Kim, "Adverse impacts of 5G downlinks on human body," in *Proc. SoutheastCon*, Apr. 2019, pp. 1–6.

[73] H. Ibraiwish, A. Elzanaty, Y. H. Al-Badarneh, and M.-S. Alouini, "EMF-aware cellular networks in RIS-assisted environments," 2021, *arXiv:2110.10311*.

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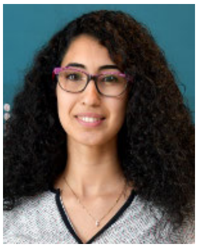

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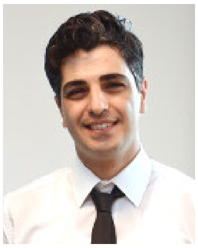

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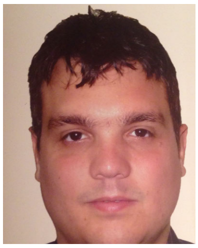

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