Received February 1, 2019, accepted February 11, 2019, date of publication March 5, 2019, date of current version March 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2902481

On Measuring Electromagnetic Fields in 5G Technology

RAFAŁ PAWLAK, PIOTR KRAWIEC, AND JERZY ŻUREK
National Institute of Telecommunications, 04-894 Warsaw, Poland

Corresponding author: Piotr Krawiec (p.krawiec@itl.waw.pl)

This work was supported in part by the Polish National Centre for Research and Development, GOSPOSTRATEG Programme, under the project 5G@PL: Implementation of 5G network in the Polish economy.

ABSTRACT At the awakening of the new 5G network as the network of services, issues related to electromagnetic fields (EMFs) will become one of the key aspects for the cost-effective establishment of the 5G infrastructure. The new 5G services will meet the rigorous demand for bandwidth through the implementation of a large number of densely located base stations operating in the millimeter-wave range. Introduction of new emission sources, working in parallel with already existing 2G/3G/4G mobile technologies, raises concerns about exceeding the admissible EMF exposure limits. This paper analyzes issues and challenges related to EMF measurements in 5G technology, which are crucial for the assessment of EMF compliance with regulatory limits. We point out that the existing methodologies, dedicated to EMF measurements in 2G, 3G, and 4G networks, are not suitable for 5G. The reason is the use of new techniques, such as massive MIMO and precise beamforming together with higher frequency bands so that the existing measurement methods can lead to significantly overestimated results when they will be applied to 5G networks. Such results, in conjunction with the restrictive legislation on the EMF limits that apply in some countries, may have the negative impact on 5G network deployment, making it difficult to achieve the intended 5G network capabilities. We also propose an alternative method of EMF exposure assessment that is based on calculations and simulations and allows obtaining an accurate estimation of the EMF distribution in the 5G environment.

INDEX TERMS 5G mobile communication, electromagnetic fields, EMF measurements.

I. INTRODUCTION

The 5th generation of mobile networks (5G) will constitute the next step in the development of telecommunications standards, significantly exceeding what the current 4G/LTE networks offer. 5G technology will meet the needs resulting from the constantly growing demands of mobile network users, as well as those imposed by innovative concepts such as connected and autonomous cars, Smart Factories or Smart Cities [4]. Compared to existing mobile networks, 5G will be able to support much more terminals (device density up to one million per square kilometer) with much higher data rates (peak rate up to 20 Gbps), extremely low latency (no more than 1 ms) and very high reliability (99,999%). In this way, 5G will ensure high Quality of Service for users, and also enable highly reliable massive communication between devices.

The requirements and technical objectives of 5G technology will be addressed by a set of new techniques and implementation approaches. Among them, the following ones have the most significant impact on the innovativeness and novelty of the 5G radio system:

- Usage of additional spectrum in the range above 3 GHz, particularly from the millimeter-wave region; it can quickly transfer a large amount of data, but over short distances due to the line of sight propagation with minimal refraction.
- Massive MIMO (Multiple Input Multiple Output) technique; in 5G, thanks to shorter wavelengths compared to the current mobile systems, it is planned to use as many as 128 to 256 integrated antennas and more than 64 integrated transceivers combined into one system. Massive MIMO with beamforming and beamsteering capabilities (a.k.a. 3D beamforming) creates an active antenna system that can emit strong and highly focused beams following the specific users. This results in significantly higher spectral efficiency since the

The associate editor coordinating the review of this manuscript and approving it for publication was Muhammad Imran.

technique enables reuse of frequency channels in the space domain.

- Strong infrastructure densification by the deployment of small (micro-/pico-/femto-) cells in high user density areas such as shopping malls or public space in city centers. This will also bring a significant gain in spectral efficiency.
- Use of Multi-Radio Access Technology (multi-RAT). Multi-RAT is in line with the current trend for aggregating different radio solutions into a combined platform to decrease wireless interferences and save energy consumption [11]. It provides integration of 5G network with other systems, such as 2G/3G/4G networks or Wi-Fi. With multi-RAT, terminals will be able to automatically obtain the best connection with the use of the optimum interface at a given moment, depending on user requirements and the current network conditions.

In 2018 there was a significant milestone in the development of 5G technology. 3GPP announced specifications for 5G Non Standalone Access (NSA) in March 2018, as well as 5G Standalone Access (SA) in September 2018. In this way, the forthcoming process of 5G commercialization will be able to proceed along two paths: as an upgrade of existing 4G networks assuming NSA option, and also as independent deployments of 5G New Radio (NR) infrastructure.

However, one of the factors that can have an important influence on the widespread deployment of the 5G networks within the commonly expected timeframe (i.e. 2020-2025), are the issues related with radio frequency (RF) electromagnetic fields (EMF). Exposure limits imposed on EMF may hinder the installation of further radio transmitters, especially in countries with more restrictive EMF regulations, such as Poland or Italy. It is worth mentioning that 5G will constitute a heterogeneous network composed of overlapping cells. Macro-cells working on spectrum below 1 GHz (e.g. 700 MHz) will establish the coverage layer that ensures wide coverage on rural and suburban areas, and also supports IoT services in deep indoor scenarios. In turn, small cells will exploit spectrum between 1 GHz and 6 GHz (in particular frequency carriers in the range 3.3-3.8 GHz) to address the combination of coverage and capacity requirements. They will be supported by pico-cells operating in frequency bands above 6 GHz (in the range 24-28 GHz first) to meet scenarios requiring ultra-high data rates. Moreover, multi-RAT may imply coexistence of different radio technologies in a given area. All these radio transmitters contribute to a cumulative EMF exposure. As shown by case studies carried out by GSMA [10], and also in the survey on EMF measurements in Europe performed by Sagar *et al.* [9], there are multiple locations where the EMF limits imposed by law are already almost fully utilized. Such situations obstruct the further development of the current mobile networks, and the more they will hamper the installation of new 5G radio transmitters.

In addition to the EMF exposure limits, public concern about the negative impact of radio frequencies on human health may be also an important factor affecting widespread implementation of the 5G infrastructure. Attention is particularly focused on higher frequencies, since millimeter-waves energy is mostly absorbed in human skin, and the mm-wave bands will be used to establish a dense structure of small pico-cells resulting in the installation of a large number of new radio transmitters. Consequently, some members of society are frightened that 5G will expose the population to new sources of dangerous radio frequency radiation.

For these reasons, effective measurements of electromagnetic fields are essential for both, the deployment of 5G networks and their later operation. Proper measurement methodology will enable monitoring of the EMF intensity, allowing government bodies as well as local communities to control whether EMF values are at a safe level.

This paper discusses the EMF measurements aspects related to 5G technology. Measurement of EMF value and assessment of EMF exposure compliance with the permitted limits, is a complex and not fully recognized issue in the case of 5G. This results from the new key 5G techniques such as massive MIMO and beamforming, as well as higher frequency bands that are crucial for providing the extremely high data rates but require new propagation models. Therefore, the measurement methodology used so far for the current generations of mobile networks (2G, 3G and 4G) may not be applicable for EMF evaluation after 5G deployment. Our contribution is also the proposal of an alternative method of EMF exposure assessment in the vicinity of 5G base stations. The new approach method is based on calculations and simulations that allow the determination of continuous EMF distributions. Due to the anticipated distance between the users and the antennas in the 5G network, we suggest estimating the EMF distribution not only in the far field zone (as it is usually done so far), but also extending it with new features of the appropriate model specific to the reactive and radiation near-field zone (based on spherical-cylindrical propagation model). We point to use digital maps of the terrain and existing buildings, and to take into account propagation phenomena.

The article is organized as follows. In the next section we present an overview of international and national EMF policies and regulations. We focus on Poland as an example of a country with more restrictive EMF exposure limits with respect to generally recognized international guidelines. Section III deals with methodologies for measuring EMF in existing mobile networks with different standards: GSM (2G), UMTS (3G) and LTE (4G). Next, we discuss aspects of EMF measurements in 5G networks, including challenges and open issues related with new techniques and mechanisms incorporated into 5G technology, and describe the proposed method for EMF exposure assessment in 5G. At last, the final section concludes the article.

II. EMF REGULATION POLICIES

Sources of natural non-ionizing electromagnetic radiation, expressed in the form of the electromagnetic field, are connected with the Earth, the Sun and atmospheric phenomena. Along with the development of civilization, as a result of the manufacture and use of various types of electrical devices, additional sources of artificial EMF have appeared. Excessive EMF exposure results in known adverse health effects, therefore appropriate legislation has been developed to protect people and the environment against the harmful effects of EMF.

A significant increase in interest in EMF occurred with the development of GSM mobile networks and the related installation of a large number of base stations emitting radio signals. In the early 1990s, the World Health Organization (WHO) initiated research work on the biological effects of radio frequency waves. In 1998, associated with WHO the International Commission on Non-Ionizing Radiation Protection (ICNIRP) defined science-based guidelines for limiting exposure to electric, magnetic and electromagnetic fields [3]. The ICNIRP guidelines form the basis for different recommendations on EMF exposure limits developed, among others, by WHO and International Telecommunications Union (ITU) and addressed to governments. It must be noted that ICNIRP continuously monitors scientific research on the effects of EMF, to ensure the human exposure guidelines are up to date.

The Council of the European Union (EU) has provided Recommendation 1999/519/EC of 12 July 1999 [2] that contains general-public reference levels of exposure, depending on the frequency range, that shall be considered as limit values. The reference levels are generally intended to be spatially averaged and refers to EMF values averaged over a period of six minutes in accordance with ICNIRP recommendation [3]. The reference levels in the radio frequency range are determined by measurable quantities, including: RMS (Root-Mean-Square) value of the electric field strength E in units of *V/m,* and the equivalent plane-wave power density S in units of W/m^2. Unperturbed RMS limit values for radio frequencies, defined by ICNIRP and included in the 1999/519/EC recommendation, are listed in Table 1.

TABLE 1. **Restrictions for EMF exposure – ICNIRP guidelines.**

Frequency f [MHz]	E [V/m]	S [W/m^2]
10 ÷ 400	28	2
400 ÷ 2 000	1,375 × √f	f/200
2 000 ÷ 300 000	61	10

The ICNIRP guidelines are accepted in many countries around the world, including most EU members. However, in some countries own legal regulations relating to the protection of human and the environment against the influence of EMF have been adopted. In Austria, Denmark, Latvia, Netherlands, Sweden and the United Kingdom, there are milder restrictions on protection against EMF exposure compared to ICNIRP limits, or even such regulations are not imposed by law. On the other hand, Belgium, Bulgaria, Croatia, France, Greece, Italy, Lithuania, Luxembourg and Poland, have approved more restricted regulations, at the national level (e.g. Poland) or in certain regions (for example, Brussel in Belgium or Paris in France). It should be emphasized that Bulgaria and Poland have the strictest requirements for admissible EMF levels. For example, in Poland limit values of the electric field strength E and the power density S, just as in Recommendation 1999/519/EC, depend on the frequency range, although the frequency ranges are slightly different. However, for frequencies above 2 GHz, the power density limit established in Poland (0,1 W/m^2) is a hundred times lower than the power density limit stated in ICNIRP guidelines (10 W/m^2) – see appropriate values in Table 1 and Table 2. The same limit applies in Bulgaria. The restriction of 0,1 W/m^2 for power density also refers to Italy, but it has significance only for areas close to houses, schools or playgrounds.

TABLE 2. **Restrictions for EMF exposure – Polish regulations.**

Frequency [MHz]	E [V/m]	S [W/m^2]
3 ÷ 300	7	*not applicable*
300 ÷ 300 000	7	0,1

Moreover, according to Electronic Communications Committee Recommendation (02)04 [24], EMF measurements in Poland should be performed at a height of 1.5 m above ground level or above floor level, taking as a measurement result the value that is averaged over any six minutes (in accordance with ICNIRP and Recommendation 1999/519/EC guidelines).

The legal regulations regarding environmental protection in Poland indicate that the measurements have to be carried out in vertical measuring lines, along the main and auxiliary directions of radiation measurements, as well as on balconies and terraces on which people can stay, and in case of buildings – in the middle of rooms and in window openings from the EMF source side. It has been determined that measurements in the vicinity of radio communication installations, in the assumed vertical measuring lines, should be made at heights from 0.3 m to 2.0 m above the ground surface or above other surfaces on which people may stay (above floor level in the case of measurements in buildings), taking, as a result, the maximum level of measured EMF. In contrast to the Recommendation 1999/519/EC, the results of EMF measurements are not averaged –either during the time (long-term or short-term) nor spatially. Thus, the restrictions adopted in Poland for the levels of EMF, e.g. produced by installations of mobile networks, are more stringent than reference levels defined in Recommendation 1999/519/EC and adopted for direct application in many Member States of the European Union.

A. IMPACT OF RIGOROUS EXPOSURE LIMITS ON 5G DEPLOYMENT

Adoption of policy to limit EMF exposure that relies on the exposure levels significantly lower than ICNIRP reference levels has a negative influence on the cost of deployment and performance of 5G networks, and could hamper the process of their introduction and the development of 5G infrastructure. Stricter limits on EMF exposure may have the following consequences:

- Required transmit power reduction causes cell range degradation (in the case of Poland, approximately from 280 m to 56 m). This enforces high infrastructure density, which greatly escalates costs and complexity of the 5G network deployment. According to a study presented in [23], current EMF regulations will impose the installation of seven times more 5G base stations by 2025, compared to the number of base stations installed in accordance with Recommendation 1999/519/EC.
- In case of 5G base stations operating in millimeter waves, for example in Poland the acceptable distance of human from the transmitter would be approximately 11 meters assuming operation with maximum transmit power. This makes practically impossible to create 5G pico-/femto-cells by installing base stations on street lamps, bus shelters and other similar objects of urban space (in countries that are in accordance with ICNIRP guidelines, the distance would be approximately 1.1 m).
- Inability to share an infrastructure (cell sites) with existing mobile technologies, since stricter EMF limits do not allow installation of another radio antennas.

III. METHODOLOGY FOR MEASURING EMF

The evaluation of compliance with the permissible EMF exposure in the vicinity of a base station is achieved by measuring the levels of EMF produced by equipment installed on site, and then comparing the obtained results with appropriate reference levels constituting limit values. Measurements are usually performed in the far field area. In this area the field has the character of a plane wave, the vectors of the electric field E and the magnetic field H are perpendicular to each other, and the power density S is related to the electric field strength E by the free space impedance $Z_0 = 120\pi$ $[\Omega]$ according to the following formula:

$$S = \frac{E^2}{Z_0} = \frac{E^2}{120\pi} \tag{1}$$

The far field area boundary R is determined by the formula:

$$R > \frac{2D^2}{\lambda} \tag{2}$$

where D is the maximum antenna dimension, and λ is the wavelength corresponding to the appropriate frequency.

The selection of the measurement equipment is required to guarantee the appropriate operating frequency range, sufficiently high sensitivity and dynamic range, adequately to the measured EMF. The measurement equipment shall be calibrated as well.

Techniques of transmitting radio signals change with the development of services in radiocommunication networks. For example, in the case of digital radiocommunication networks such as UMTS and LTE, the power of transmitters supplied to antennas depends on the telecommunications traffic load carried by the base station (BS), so it varies over time. Moreover, this variability is of a random nature. This results in the fact that the distribution of EMF intensity in the vicinity of a base station does not fall within the framework of the deterministic model. On the other hand, it can be probabilistically described with software tools appropriate for mathematical statistics.

A. BROADBAND MEASUREMENT

Broadband measurement method enables determination of the RMS value of the electric field strength E and power density S in the vicinity of a base station. As noted earlier, the measurements are usually performed in the far field area i.e. in the area where the field strength E and power density S are interrelated with each other by the formula (1), therefore to an unambiguous EMF determination, it is enough to determine the RMS value of the electric field strength E. Next, the power density S can be calculated. Typical measurement equipment consists of an electric field strength meter connected with broadband isotropic measuring antenna, i.e. a probe. The total broadband EMF measurement results of the E_{sum} and S_{sum} are in fact the sum of all components E_k and S_k from n signals received by the measurement antenna in the frequency range determined by its construction, according to the following formulas:

$$E_{sum} = \sqrt{\sum_{k=1}^{n} E_k^2} \tag{3}$$

$$S_{sum} = \sum_{k=1}^{n} S_k \tag{4}$$

In the case of broadband EMF measurements, the identification of frequency components is not possible.

Measurement points should be chosen in those representative places where the highest EMF exposure levels are supposed to occur. All possible sources of emissions should be taken into account. The actual measuring points can be determined either empirically on the basis of preliminary measurements (with the measurement equipment attentively moved in the horizontal and vertical plane) or on the basis of calculations of the theoretical EMF distribution. The probe should be moved away from any metal surfaces because they disturb the EMF distribution and, in general, they are the source of the secondary EMF as a result of the coupling effect. In addition, if national legal regulations permit such a methodology, spatial averaging of electric field strength E and power density S should be performed, since it provides a better assessment of the exposure of the entire human body to EMF. The spatial average value of the electric field strength $E_{spatial\_average}$ and the spatial average value of the power density $S_{spatial\_average}$ are determined based on the formulas:

$$E_{spatial\_average} = \sqrt{\frac{\sum_{i=1}^{N} E_i^2}{N}} \tag{5}$$

$$S_{spatial\_average} = \frac{\sum_{i=1}^{N} S_i}{N} \tag{6}$$

where N is the total number of measurement points, while E_i and S_i are RMS values of electric field strength E and power density S (respectively) at the i-th measurement point. The spatial averaging over nine points of space was adopted as the reference spatial averaging method. Relevant details about spatial averaging can be found in the EN 62232:2017 standard [1].

B. FREQUENCY-SELECTIVE MEASUREMENT

The use of frequency-selective measurement equipment allows selective measurements in the frequency domain and enables determination of the EMF level in a precisely defined frequency range. This improves the situation regarding the identification of EMF frequency components and, as a result, identification of, for example, a specific base station.

Obtained results of measurements, both broadband and frequency-selective, reflect the level of EMF occurring in the vicinity of a base station during its normal operation. In fact, due to the momentary telecommunications traffic load carried by the base station, the EMF level changes over time.

The determination of the maximum EMF level in the vicinity of the GSM base station can be carried out using frequency-selective measurement equipment [7]. For this purpose, the *Broadcast Control Channel (BCCH)* signal of the specified base station is used, because the *BCCH* signal is always broadcasted with constant and maximum power. E_{BCCH} level can be determined after tuning the measuring equipment to the appropriate GSM carrier frequency, on which, in a specific cell sector, the *BCCH* signal is transmitted. Several carrier frequencies are typically used in each GSM cell sector. The maximum EMF level in a specific GSM cell sector is determined by the formula:

$$E_{GSM\_BS} = E_{BCCH} \times \sqrt{\alpha} \tag{7}$$

where α is the total number of carrier frequencies in one GSM cell sector. In a typical scenario there are four carriers per sector ($\alpha = 4$), therefore:

$$\begin{aligned} E_{GSM\_BS} &= E_{BCCH} \times \sqrt{4} \\ E_{GSM\_BS} &= 2 \times E_{BCCH} \end{aligned} \tag{8}$$

Measurements and calculations should be performed for all E_{BCCH} identified in a specific site under evaluation, to obtain subsequent values of E_{GSM_BS1}, $E_{GSM\_BS2}, \ldots, E_{GSM\_BSx}$. The resultant value is calculated according to the following formula:

$$E_{GSM\_max} = \sqrt{E_{GSM\_BS1}^2 + E_{GSM\_BS2}^2 + \ldots + E_{GSM\_BSx}^2} \tag{9}$$

In the vicinity of UMTS and LTE base stations, extrapolation of the obtained measurement results should be performed in order to estimate the maximum EMF levels. The basic extrapolation methods described in the EN 62232:2017 standard [1] allow determining the conditions and manner of EMF measurements so that the measurements are reliable. The determination of the maximum EMF level in the vicinity of the UMTS and LTE base station can be successfully carried out using frequency-selective measurement equipment with code domain measurements.

The determination of the maximum EMF level in the vicinity of the UMTS base station is based on the *Primary Code of the Common Pilot Channel (P-CPICH)* measurement [5]. It is known that the *P-CPICH* signal is always broadcasted in each cell sector of the UMTS network. $E_{P\text{-}CPICH}$ level can be determined after tuning the measurement equipment to the appropriate UMTS radio channel center frequency and then decoding *P-CPICH* signals in the code domain. After decoding *P-CPICH* signals sector/cell identification is possible as well. The maximum EMF level in a specific UMTS cell sector is determined by estimation of maximum traffic load carried by UMTS base station, according to the formula:

$$E_{UMTS\_BS} = E_{P\text{-}CPICH} \times \sqrt{R_{P\text{-}CPICH}} \tag{10}$$

where $R_{P\text{-}CPICH}$ is the factor defining the ratio of the maximum possible UMTS transmitter power P_{MAX} to the power of *P-CPICH* signal component $P_{P\text{-}CPICH}$. It is determined by the formula:

$$R_{P\text{-}CPICH} = \frac{P_{MAX}}{P_{P\text{-}CPICH}} \tag{11}$$

It is typically assumed that $R_{P\text{-}CPICH} = 10$, therefore:

$$\begin{aligned} E_{UMTS\_BS} &= E_{P\text{-}CPICH} \times \sqrt{10} \\ E_{UMTS\_BS} &\approx 3{,}16 \times E_{P\text{-}CPICH} \end{aligned} \tag{12}$$

Measurements and calculations should be performed for all $E_{P\text{-}CPICH}$ identified in a specific site under evaluation, to obtain subsequent values of E_{UMTS_BS1}, $E_{UMTS\_BS2}, \ldots, E_{UMTS\_BSx}$. The resultant value is calculated according to the following formula:

$$E_{UMTS\_max} = \sqrt{E_{UMTS\_BS1}^2 + E_{UMTS\_BS2}^2 + \ldots + E_{UMTS\_BSx}^2} \tag{13}$$

The determination of the maximum EMF level in the vicinity of the LTE base station is based on the *Cell-specific Reference Signals* (*CRS*) measurement [6]. *CRS* signals are always transmitted in all subframes of the *Physical Downlink Control Channel (PDSCH)*, through one, two or four of LTE base station antenna ports. E_{CRS} level can be determined after tuning the measurement equipment to the appropriate LTE radio channel center frequency and then decoding *CRS* signals in code domain. After decoding *CRS* signals, identification of active antenna ports is possible as well. The maximum EMF level in a specific LTE cell sector is determined by estimation of maximum traffic load carried by LTE base station, according to the formula:

$$E_{LTE\_BS} = E_{CRS} \times \sqrt{K_{CRS}} \tag{14}$$

where K_{CRS} is the factor that defines the ratio of the total radiated power by all active antenna ports P_{MAX} to the power of CRS signal component P_{CRS}. It is determined by the formula:

$$K_{CRS} = \frac{P_{MAX}}{P_{CRS}} \tag{15}$$

K_{CRS} factor depends on the bandwidth of the LTE channel and can be equal to: 300 for 5 MHz channel, 600 for 10 MHz channel or 1200 for 20 MHz channel. Measurements and calculations should be performed for all E_{CRS} identified in a specific site under evaluation, to obtain subsequent values of $E_{LTE\_BS1}, E_{LTE\_BS2}, \ldots, E_{LTE\_BSx}$. The resultant value is calculated according to the following formula:

$$E_{LTE\_max} = \sqrt{E^2_{LTE\_BS1} + E^2_{LTE\_BS2} + \ldots + E^2_{LTE\_BSx}} \tag{16}$$

C. UNCERTAINTY

Regardless of carefulness during the measurement campaign, each obtained measurement result is disturbed by certain random errors, caused by different components. The range of errors can be determined statistically and included in the obtained measurement result as an estimate of measurement uncertainty. The measurement uncertainty is particularly important in the assessment of compliance, e.g. with EMF limit values. Usually an expanded uncertainty u_e is used to calculate the range of magnitude in which the measured value takes its place with a predetermined probability. A probability level of 95% is typically adopted for measurement results evaluation. The range of the expanded uncertainty u_e is calculated by multiplying the interval of combined standard uncertainty u_c, corresponding to the standard Gaussian deviation, by a coverage factor k. For probability level of 95% it is assumed that $k = 1, 96$, therefore:

$$u_e = k \times u_c = 1{,}96 \times \ u_c \tag{17}$$

The combined standard uncertainty u_c is determined based on the formula:

$$u_c = \sqrt{\sum_{i=1}^{N} (c_i \times u_{xi})^2} \tag{18}$$

where N is the total number of components, c_i is the sensitivity coefficient of i-th component and u_{xi} is the standard uncertainty of i-th component. Appropriate components that create a total budget of measurement uncertainty should be taken into consideration in accordance with the provisions of EN 62232:2017 standard [1].

IV. EMF IN 5G ENVIRONMENT

It is expected that the implementation of the 5G network planned for the upcoming years will bring a significant increase in the throughput (up to 20 GB/s according to the initial ITU specification) and also a reduction of data transfer latency to 1 millisecond. The need for the frequency band required for such a high throughput will involve the need to migrate to new frequency resources, i.e. several tens of GHz (millimeter-waves). This will cause an avalanche increase in the number of micro-cells with an extremely small radius of approximately 200 m, as a result of which the micro-cells and their antennas will be located much closer to the user. The simultaneous support of several thousand devices and ensuring high reliability of radio links by avoiding interference will enforce the use of the massive MIMO technique with concurrent transmitting and receiving from an antenna matrix composed with several tens or even hundreds of antennas. At the same time, modern techniques of modulation and coding, as well as the possibility of spatial forming and directing many different antenna beams from base stations to individual users equipment devices, i.e. 3D beamforming technique, will allow reducing the power delivered to the antennas of 5G base stations [8]. The implementation of the 5G network requires the revision of the approach and development of new methods for the EMF levels determination.

The expected revisions will apply to the measurement equipment also. The development of highly specialized measurement devices is usually a long-lasting process, due to validation of the measuring functionality and obligatory calibration process. For measuring equipment this is the critical rule. Moreover, new simulation methods enabling the determination of continuous EMF distributions, taking into account the site topology and technical parameters of base stations, will become extremely important. As noted by Chiaraviglio *et al.* [21] this is an issue even at the stage of planning locations for 5G base stations.

The current methodology for determining the received EMF exposure relies on the assumption that the transmitting antennas are characterized by known, predictable radiation pattern. Moreover, it assumes a very conservative estimation that the base station is transmitting radio signals with its theoretical maximum power, as well as that the EMF distribution in the vicinity of a base station is quasi-deterministic in nature.

However, both of these assumptions are not suitable for new 5G technology. 2G, 3G and 4G networks exploit nowadays advances emitters such as 8-element dual-polarized passive antennas working in frequency bands from 0.7 GHz to 3.4 GHz. Nevertheless, the active antenna systems developed for 5G will differ significantly from those used in the current mobile systems, since they will include even 256 active antennas operating in higher frequencies (3.4 GHz to 6 GHz and 20 GHz to 60 GHz). In addition, 3D beamforming will allow steering the beam in both horizontal and vertical planes, transmitting radio signal precisely to the receiving terminal, in contrast to a constant transmission in a wide sector which takes place in 2G, 3G and 4G technologies. These features give a new look at the EMF measurement methodology in 5G networks, and imply the inability to directly use the methodologies successfully applied in 2G, 3G and 4G.

5G network will be deployed gradually, while 2G, 3G and 4G base stations will not be extinguished from day to day. In addition, EMF exposure assessment always refers to accumulated radiation emitted by various RF signal sources (e.g. DVB-T broadcasting transmitters), and not only to radiation emitted by antennas in cellular networks. Therefore, the new EMF measurement methodology should take into account all RF signal sources, including those operating in different radio communication systems that coexist in a given area.

Higher frequencies intended for arranging in 5G networks also must be considered. Such frequencies, which result in different propagation and diffraction conditions, together with 3D beamforming, lead to the new, complex radiation pattern of the 5G antenna [19]. The pattern should include an envelope of all transmitted radio beams. Therefore, the existing models used in EMF exposure assessment could be not sufficient when 5G base stations will be deployed. Extremely short distances between neighboring 5G base stations, the use of 3D beamforming and massive MIMO techniques, jointly with a very wide spectrum of utilized frequencies, will result in the necessity of reliable verification and calibration of a new model proposed for 5G EMF exposure evaluation.

The current EMF assessment regulations impose measurements with assumed theoretical maximum transmission power. However, many experimental studies that were based on large data sets collected from operational mobile networks have pointed out that in already existing 2G, 3G and 4G systems base stations output powers very rarely reach values close to the theoretical maximum [12]–[14]. For example, the results presented in [14] show that during peak load hours the 90^{th} percentile of the output power was not more than 65% for 2G base station equipped with two or more transceivers. In the case of 3G installations, the corresponding 90^{th} percentile had even lower value and did not exceed 43%. One of the reasons are advanced algorithms for dynamic allocation of network resources implemented in base stations, which allow an automatic transfer of current traffic from more-loaded to less-loaded frequency bands that require lower transmission power. As a result, radio resources of base stations are used in a balanced way. In conclusion, base stations operate over a range of output powers that are well below the maximum value and dependent on different factors varying over time, such as traffic volume that need to be transferred, signal propagation conditions and discontinuous transmissions related to time-based medium access methods.

5G systems will include highly optimized mechanisms that provide wide coverage while minimizing power consumption. As a result, the radio signal is transmitted as a narrow beam focused in the direction of user terminal solely, which will also dynamically follow the moving terminal. In addition, 5G technology will make extensive use of Time Division Duplex (TDD), and a downlink transmission will be only the fraction of time dedicated to data exchange between the terminal and the base station. For this reasons, the existing conservative methodology that assumes long-term and stable, in time and space, EMF emissions from base station antennas with maximum power in each possible direction (*maximum maximorum* EMF values), is very impractical and will lead to a significant overestimation of the measurement result and, consequently, incorrect exposure assessment in case of 5G. It must be noted that EMF exposure assessment is a legally regulated area, therefore any mistakes associated with the accepted measurement methodology (including results overestimation) may result in significant negative economic effects for mobile network operators. Hence, new methodology dedicated for 5G should accommodate two kinds of averaging: spatial and in the time domain.

Taking into account overlapping cells and multi-RAT, the methodology also needs to consider the combination of the exposure ratios from multiple frequencies and multiple signal sources. The human body is affected by cumulative EMF, therefore all transmitters, belonging to different radio technologies that coexist at a given area, should be included in the cumulative EMF exposure level. Furthermore, the complexity of EMF compliance assessment for 5G base station increases due to different random factors, such as a number of possible beams that are simultaneously transmitted to mobile terminals and the distribution of connected devices within the cell causing beams variability in space.

An alternative way to assess EMF exposure is a new approach method that exploits simulations and calculations. This method allows the determination of continuous EMF distributions without the need for performing costly on-site measurements. The new method needs to take into account a topology of the evaluated location as well as numerous technical parameters of involved base stations. The fundamental issue for this method is the accuracy of the simulation models. The complexity of the utilized propagation model, including consideration of buildings existing in the vicinity of the base station, will have direct impact on the simulation accuracy. In general, the more complex the model is, the more accurate simulation.

Due to the expected dense structure of a network of 5G base stations, and a significant reduction in the distance between the antennas and users, the estimation of EMF distribution in the far field zone only that based on radiation pattern (as it has been usually done so far), will not be sufficient. This implies the extension of the EMF estimation by new features of an appropriate model specific to the reactive and radiation near-field zone, based on spherical-cylindrical propagation model. However, this does not exhaust the subject matter. It will also be essential to use digital maps of a terrain and existing buildings in 3D format, with a sufficiently precise grid (for example, 1 m × 1 m). The new model should also take into account propagation phenomena (diffraction, reflection and interference of electromagnetic waves), which result from applied GHz frequencies and the impact of existing buildings.

As a summary, it should be stated that calibrating the simulation model will be a task requiring the highest precision and pay of attention. In this case, a crucial element is the provision of accurate input data that addresses all relevant factors and 5G mechanisms. Development of a standardized approach for at least the most common 5G antennas will significantly contribute to the facilitation of EMF compliance evaluation process.

Some of the above mentioned factors have been included in the new version of the EN 62232, which was published in 2017 [1]. The standard provides an enhanced methodology for EMF exposure assessment that defines the actual maximum power as the 95th percentile of the measured values instead of the theoretical maximum value. In this way, the proposed methodology takes into account the long-term results of spatial multiplexing introduced by massive MIMO mechanism, and also intermittent transmission related to TDD medium access.

Nevertheless, precise and effective methods dedicated to 5G, both measurement-based and computational, are still being an open problem under evaluation by international organizations. Engaged standardization bodies: IEC Technical Committee 106 (TC106) [16] and IEEE Technical Committee 34 (TC34) [17], have established IEEE/IEC joint working groups that develop a dual logo standards in the area of EMF compliance assessment for 5G technology. Also ITU-T Study Group 5 (SG5) is closely collaborating with the two above technical committees to harmonize development of the standards related to EMF exposure measurement in 5G networks.

Several approaches, with the aim of the definition of proper models for estimating EMF in 5G, have been already proposed by the research community. Thors *et al.* [15] present a model for time-averaged estimation of the actual maximum power (defined as 95th percentile) for the 5G base stations. The model is based on a statistical approach and considers such factors as base station utilization, massive MIMO antenna, TDD and spatial distribution of mobile terminals. Presented results show 15% gain compared to the traditional conservative approach with theoretical maximum power. Baracca *et al.* [20] propose another statistical approach for assessment of EMF exposure generated by massive MIMO systems. It exploits the three dimensional spatial channel model standardized by 3GPP. The authors demonstrate that the proposed solution, when compared to the traditional conservative method, introduces almost 50% reduction of the compliance boundaries in the vicinity of a base station, i.e. the zone in an environment that cannot be accessed by the general public.

Moreover, Chiaraviglio *et al.* [21] consider the problem of planning 5G base station locations under EMF exposure limits. Compliance with EMF exposure limits, which is taken into account at the stage of planning the location of base stations, will be critical in the case of 5G networks. Performed analysis indicates that due to EMF saturation effect, the process of installing new 5G transmitters may be very challenging, in particular in dense urban areas. The authors analyze also the guidelines for 5G network planning process under strict EMF exposure limits, and conclude that EMF-aware 5G planning is a very complex process, which should take into account such aspects as:

- Modeling of the 5G RAT;
- Computation of the EMF levels;
- Integration of the EMF limits;
- Modeling of network topology;
- Modeling of traffic demands and Quality of Service perceived by users.

Development of cost-effective instruments to measure millimeter wave radiation, constitutes a separate issue related to EMF measurements. According to our research, broadband EMF measurement equipment with E field probes on frequencies up to 90 GHz, intended for general-public EMF measurements, is already available. On the other hand, frequency-selective and code-selective measurement equipment dedicated to the frequencies above 6 GHz is not yet offered, unfortunately. System design of such equipment is challenging considering its complexity and high frequencies. The novel approach for real-time in-situ monitoring of far-field radiation properties relies on information obtained from surface waves and EMF in close proximity of the radiating antennas using Proximal-Field Radiation Sensors (PFRS). However, the design of PFRS dedicated to millimeter waves is a challenging task since PFRS substrate thickness is comparable to the wavelength, what can initiate the excitation processes by the radiating antennas [22].

Constant, real-time monitoring of EMF levels is very important, if we take into account observed some public concern about the impact of 5G transmitters on human health. Providing the community with information demonstrating that current EMF levels are below the allowed limits, will have a positive effect on the reduction of worries about health. Such information should be gathered by a distributed system, which is, for example, equipped with stationary monitoring probes and continuously monitors EMF values in different locations, especially urban zones characterized by a dense distribution and dynamic load changes of base stations. The system should include all EMF emission sources operating in radio frequency ranges, that are installed at a given area. In this way, the community members will be given the possibility to check at any time the EMF exposure levels at selected locations, for example by means of a publicly accessible website.

Moreover, such EMF monitoring system should also speed up the installation process of new 5G transmitters, as obtaining an installation permit by the mobile network operator will not require time-consuming EMF measurements in each case. Taking into account the expected large number of 5G base stations, on-site measurements for each installation could result in a significant delay in the permitting process, slowing down the development of the 5G network accordingly.

V. CONCLUSION

5G technology has been designed for the highest possible energy efficiency. Comparing to existing mobile networks, 5G allows transferring more data and handling more users consuming the same power. Nevertheless, because of cells and technology overlapping, as well as a multitude of base stations situated at short distances from each other, there is a serious concern about optimal planning of 5G base stations deployment due to strict regulation limits on EMF levels.

Therefore, the measurement of EMF values and their evaluation for compliance with the permitted limits, are of major importance in case of forthcoming 5G network deployment. However, development of the proper methodology that is suitable for 5G, is a challenge, while the traditional conservative methodologies dedicated for existing mobile systems 2G, 3G and 4G, can provide to very ineffective results when they will be applied to 5G system. The new 5G methodology should consider such factors as massive MIMO and precise beamforming, frequency bands in millimeter wave region, new antenna radiation patterns, TDD access to the medium, number of possible simultaneous beams and distribution of terminals associated with given base station causing movement of beams in the space.

In order to ensure effective multiplexing in spatial and time domain, massive MIMO together with TDD will be highly exploited in future 5G systems. Therefore, it is likely that the most appropriate model for the EMF estimation will be based on a statistical approach. Although some solutions have already been proposed, their intensive evaluation and testing, performed in real networks, are necessary. They will allow precise determining of model inaccuracy and discovering the set of parameters appropriate for using the model in various EMF measurement scenarios.

REFERENCES

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

[2] "Report on the implementation of the council recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz–300 GHz) (1999/519/EC) in the EU member states, release 2.1," Eur. Commission, Brussels, Belgium, Project no. SI2.489570-SANCO/2OO7/C7/06, May 2008.

[3] ICNIRP, "Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 74, pp. 494–522, Oct. 1998.

[4] J. M. Batalla *et al.*, "Efficient media streaming with collaborative terminals for the smart city environment," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 98–104, Jan. 2017.

[5] Scuola Universitaria Professionale della Svizzera Italiana, Dipartimento Tecnologie Innovative, Alta Frequenza, "Basis for a UMTS measurement recommendation," Project no. 08R2-HFumts, Apr. 2004.

[6] Federal Office of Metrology METAS, Section Electricity, "Measurement method for LTE base stations," METAS, Bern, Switzerland, METAS-Rep. 2012-218-808, Tech. Rep., May 2012.

[7] *Recommendation ITU-T K.83. Monitoring Field Strengths of Electromagnetic Fields*, document E 36701, International Telecommunication Union, (ITU), Series K: Protections Against Interference, 2011.

[8] *5G Technology and Human Exposure to RF EMF*, document E 42102, International Telecommunication Union (ITU), Series K: Protections Against Interference, 2017.

[9] S. Sagar *et al.*, "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, 2018.

[10] *Arbitrary Radio Frequency Exposure Limits: Impact on 4G Network Deployment*, GSMA, London, U.K., Mar. 2014.

[11] J. M. Batalla *et al.*, "On cohabitating networking technologies with common wireless access for home automation systems purposes," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 76–83, Oct. 2016.

[12] P. Joshi, M. Agrawal, B. Thors, D. Colombi, A. Kumar, and C. Törnevik, "Power level distributions of radio base station equipment and user devices in a 3G mobile communication network in India and the impact on assessments of realistic RF EMF exposure," *IEEE Access*, vol. 3, pp. 1051–1059, Jul. 2015.

[13] A. Burgi, D. Scanferla, and H. Lehmann, "Time averaged transmitter power and exposure to electromagnetic fields from mobile phone base stations," *Int. J. Environ. Res. Public Health*, vol. 11, no. 8, pp. 8025–8037, 2014.

[14] D. Colombi *et al.*, "Downlink power distributions for 2G and 3G mobile communication networks," *Radiat. Protection Dosimetry*, vol. 157, no. 4, pp. 477–487, Dec. 2013.

[15] 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.

[16] *IEC Technical Committee 106: Methods for the Assessment of Electric, Magnetic and Electromagnetic Fields Associated With Human Exposure*. Accessed: Dec. 19, 2018. [Online]. Available: https://www.iec.ch

[17] *IEEE ICES International Committee on Electromagnetic Safety*. Accessed: Dec. 19, 2018. [Online]. Available: https://www.ices-emfsafety.org/committees/

[18] *ITU-T Study Group SG5: Environment, Climate Change and Circular Economy*. Accessed: Dec. 19, 2018. [Online]. Available: https://www.itu.int/en/ITU-T/studygroups

[19] 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.

[20] P. Baracca, A. Weber, T. Wild, and C. Grangeat, "A statistical approach for RF exposure compliance boundary assessment in massive MIMO systems," in *Proc. 22nd Int. ITG Workshop Smart Antennas (WSA)*, Bochum, Germany, Mar. 2018, pp. 1–6.

[21] L. Chiaraviglio *et al.*, "Planning 5G networks under EMF constraints: State of the art and vision," *IEEE Access*, vol. 6, pp. 51021–51037, 2018.

[22] A. Safaripour, B. Asghari, and A. Hajimiri, "Proximal-field radiation sensors for millimeter-wave integrated radiators," in *Proc. IEEE Radio Freq. Integr. Circuits Symp. (RFIC)*, Philadelphia, PA, USA, Jun. 2018, pp. 256–259.

[23] M. Godlewski, M. Steiger, R. Schicht, and A. Bernold, "Impact of power density limits (PDL) on wireless connectivity: Are Poland threatening to delay 5G development?" (in Polish), The Boston Consulting Group BCG, Boston, MA, USA, Jul. 2018. [Online]. Available: http://image-src.bcg.com/Images/Effects-Polish-Power-Density-Limits_tcm78-196349.pdf

[24] *Measuring Non-Ionising Electromagnetic Radiation (9 kHz-300 GHz)*, document ECC Recommendation (02)04 (Revised Bratislava 2003, Helsinki 2007), ECC/REC/(02)04. ECC CEPT, 2007.

RAFAŁ PAWLAK received the master's degree in telecommunications (radiocommunication and radiolocation) from the Faculty of Electronics and Information Technology, Warsaw University of Technology, in 2002.

He has been an employee of the National Institute of Telecommunication (NIT), Warsaw, since 2001. He is a Leading Specialist with the Equipment and Systems Testing Department. He is also a Technical Manager with the accredited Telecommunications Equipment Research Laboratory (AB121) and an employee of the Notified Body 1471. From the beginning of his professional career, he was associated with radio equipment research to meet the essential requirements of the Radio Directive and the EMC Directive. He has extensive experience in the field of electromagnetic field measurements. He is the co-author of the NITs' methodology the electromagnetic field measurements of selective in the code domain in the vicinity of cellular base stations.

Mr. Pawlak is a member (representative with the right to vote) of the Technical Committee in the Polish Committee for Standardization. He was an Expert with the Polish Center for Accreditation in the area of auditing notified bodies within the scope of the radio directive.

PIOTR KRAWIEC received the Ph.D. degree in telecommunications from the Warsaw University of Technology (WUT), Poland, in 2011. He is currently an Assistant Professor with the Internet Technologies and Applications Department, National Institute of Telecommunications, Poland, and concurrently holds a research position with WUT. His research interests include mobile telecommunication systems (3G, 4G, and 5G), software-defined networking, Internet protocols and applications, wireless communications, and the Internet of Things.

JERZY ŻUREK received the M.Sc. degree from Gdynia Maritime University, Gdynia, Poland, and the Ph.D. degree from the Gdańsk University of Technology, Gdańsk, Poland, in 2005.

He has been the Director with the National Institute of Telecommunications, since 2014. Since 2005, he has cooperated with the Volpe Research Center, U.S. Department of Transportation, Boston, MA, USA, as well as with the University of New Hampshire, concretely with the Critical Infrastructure Dependability Laboratory. He has participated in several European projects, among them INTERREG IV EfficienSEA, where he coordinated the work Akademia Morska partner. He has authored or co-authored more than 100 publications published in national and international journals and conference proceedings. His research interests include distributive frequency range and frequency hopping systems (both terrestrial and satellite), mobile systems (3G, 4G, and 5G), software-defined radio, security in radio systems, embedded systems, wireless networking, ad hoc wireless sensor networks, and cognitive radio.

• • •