Radio Frequency EMF Measurements and Exposure Assessment from 5G Outdoor Base Stations

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***Abstract*—This paper presents preliminary results of radio-frequency electromagnetic field (RF-EMF) measurements in outdoor environments. The purpose is to measure and evaluate the exposure levels of general public from fifth generation (5G) base stations, and compare them with the enforced national and international guidelines. Frequency selective measurements have been performed in diverse urban and rural locations between 27 MHz and 6 GHz, comparing the 5G emissions with other cellular or broadcast exposure levels. The electric field, explicitly from 5G emissions, varies in the range of 0.14-0.57 V/m, and 0.19-4.10 V/m, in urban and rural locations, respectively. The maximum 5G emission, in terms of power density (44.6 mW/m^2), is measured in rural areas and corresponds to about 0.4% of the legislated limits in the European Union. The inherent structure of the 5G networks corroborate the observed difference in exposure levels between urban and rural areas. The maximum recorded Total Exposure Ratio (TER) is about (27.71±12.06)·10^{-3}, being consistent with the enforced limits. Finally, 5G emissions are found to contribute about 12% to the total exposure levels.**

***Index Terms*—5G, human exposure, outdoor antennas, total exposure ratio (TER).**

I. INTRODUCTION

The advent and growth of the fifth generation (5G) cellular networks are anticipated to provide ubiquitous services to the end-users, digitizing their daily life in an unprecedented way [1]. This omnipresent deployment entails a cell densification with the presence of a large number of small-cell antennas [2]. Consequently, this ultra-dense establishment is expected to make the human outdoor environment susceptible to increased radio-frequency electromagnetic field (RF-EMF) levels. This may initiate major concerns about the exposure levels and the safety of the general public. The establishment of the various networks to monitor the outdoor RF-EMF levels [3], has not managed to relieve people's exposure concern, especially from the recently deployed 5G antennas. It is thus pivotal to measure and evaluate the exposure levels from outdoor 5G base stations operating in the sub-6 GHz band (FR1), compare the measured levels with the imposed national and international limits and yield valuable information about the safety of the general public.

There are not many research efforts in the existing literature that measure or estimate RF-EMF levels from 5G antennas [4]-[9]. However, the majority of those campaigns are focused on experimental level measurements, and methods, related to 5G antennas that exploit massive multiple-input-multiple-output (MIMO) or beamforming configuration [5]-[8].

Currently, the 5G network in Greece is deployed in major cities and selected rural areas, operating in the sub-6 GHz band. According to the operators, it is expected to reach population coverage of 80% by the end of 2022. However, the installed 5G antennas do not yet exploit neither massive MIMO, nor beamforming technology. The established base stations operate in the 3.5 GHz band with channel bandwidth of 100 MHz in time-division duplex (TDD) configuration. Additionally, the 700 MHz band has been also allocated for 5G services, although it is not currently operational.

This work delivers preliminary RF-EMF measurement results from 5G antennas in various outdoor locations. More specifically, frequency selective measurements have been performed between 27 and 6000 MHz, thus recording, apart from 5G emissions, additional RF-EMF sources for comparison purposes (e.g., other cellular or broadcast emissions). The measurement results are assessed and all the relative exposure parameters are calculated and compared with the enforced limits. Finally, the results are expected to demonstrate the influence of each emitting source on the total exposure levels.

The rest of the paper is structured as follows. The measurement locations, equipment, and methodology are outlined in Section II. The exposure regulations that are currently applied are presented in Section III. The calculated exposure emissions are presented and discussed in Section IV, followed by a brief summary in Section V.

II. MATERIALS AND METHODS

A. Measurement environment

Exposure measurements were carried out around 8 distinct base stations, out of which 5 were deployed in urban, and 3 in rural environment. A total number of 48 different spots were selected to perform recordings around each base station (6 spots per base station) at distances from 10 to 350 m. All the measurements positions were located on the street level. It should be pointed out that the selected base station antennas, apart from 5G service at 3.5 GHz, supported additional cellular services at 800 (4G-LTE), 900 (3G-GSM), 1800 (4G-GSM), 2100 (4G-UMTS), and 2600 MHz (4G-LTE). Each base station incorporates four 90-degree beamwidth sectoral antennas so as to provide omnidirectional coverage.

TABLE I. FREQUENCY BANDS AND EXPOSURE LIMITS FOR THE GENERAL PUBLIC [17], [21].

Frequency Band [MHz]	**Indicative Service**	**$E_{\text{lim},i}$ [V/m]**			**$S_{\text{lim},i}$ [W/m^2]**		
		EU*	**GR***		**EU**	**GR**	
			0.7×EU	0.6×EU		0.7×EU	0.6×EU
10-400	FM, VHF-TV, TETRA, DMR	28	23.4	21.7	2.0	1.4	1.2
400-2000	DVB-T, UHF-TV, LTE-800 GSM-900, GSM-1800, UMTS	$1.375\sqrt{f}$	$1.15\sqrt{f}$	$1.065\sqrt{f}$	$f/200$	$f/286$	$f/333$
2000-6000	LTE-2600, WiFi 2.4/5 GHz 5G-3.5 GHz	61	51	47.2	10	7.0	6.0

*EU: European Union, GR: Greece

The antennas in urban areas were all placed at the top of 15-m premises (corporate or residence), surrounded by five or six storey buildings (mainly residences). In rural locations the antennas were placed on top of low-height hills, isolated and distant from residential areas. Care was taken that every measurement spot was situated within the main lobe of one sectoral antenna, thus ensuring uniform field strength recordings. The field perturbation due to random reflections from moving obstacles in the proximity of the recording location (usually occurred in urban areas), was taken into consideration as an uncertainty factor, as described in Section II-B.

B. Measurement equipment, methodology and parameters

The measurements were performed between 27 and 6000 MHz exploiting SRM-3006 frequency selective radio meter by Narda GmbH (Pfullingen, Germany). The measurement method was also similar with the one adopted by Ofcom [4], where recordings from 5G base stations were collected at different cities throughout United Kingdom. Two different sensor probes were used in order to cover the entire frequency range (27 MHz - 3 GHz and 420 MHz - 6 GHz). Combining the measurement recordings, the entire frequency range was segmented into 17 different sub-bands, which, apart from 5G, included all the known supported services that are indicated in Table I. The equipment combined a triaxial electric field probe with isotropic sensing capability that was attached to the main unit through a 1.5-m cable.

The measurements were based on the methodology enforced by the Greek legislation [10], which adhere to the ISO/IEC 17025:2017 standard [11]. The adopted measurement procedure is in accordance with international standards [12]-[14]. Care was taken so that the measurement spot was located in the far-field of the base station antenna. Furthermore, the measurement equipment was also calibrated according to the ISO/IEC 17025:2017 standard. Taking into consideration a 95% confidence interval, the expanded uncertainty (being frequency dependent), ranged between 41.9% and 46.9%. These values accounted for Type A and Type B uncertainties [15], the uncertainty for the proximity of the operator (13.8% for a 1.5-m cable), and the random reflection uncertainty (5.75%), for any moving obstacles close to the sensor (e.g., walking pedestrians, cars, buses etc.). The last two uncertainty parameters can be calculated according to [16], and are independent of frequency. It should be mentioned that the reflection uncertainty is taken into account only in urban areas during postprocessing.

In every measurement location the triaxial sensor was placed on a wooden tripod and recordings were taken at 1.1, 1.5, and 1.7 m above the ground [13]. Each recording was time-average for a period of six minutes at each height [17]. During postprocessing the electric field strength values were spatially-averaged for the three selected heights. The averaged electric field $\overline{E}_i$, for the i-th sub-band is given by

$$\overline{E}_i = \sqrt{\frac{1}{N}\sum_{j=1}^{N} E_{i,j}^2} \tag{1}$$

where $E_{i,j}$ is the electric field value (in V/m) of the i-th frequency sub-band at the j-th height ($N = 3$). Since the far-field assumption stands, as mentioned previously, the power density (in W/m^2) can be calculated as

$$\overline{S}_i = \overline{E}_i^{\,2} / Z_0 \tag{2}$$

where Z_0 = 377 Ohms denotes the free-space wave impedance, and $\overline{S}_i$, stands for the spatially averaged power density at the i-th frequency sub-band. Accordingly, the total electric field (E_{total}) for the entire measured frequency range (27 MHz – 6 GHz) is given by

$$E_{total} = \sqrt{\sum_{i=1}^{K=17} \overline{E}_i^{2}} \tag{3}$$

where $\overline{E}_i$ is the spatially-averaged electric field at the i-th sub-band. In order to determine the aggregate exposure level from the diverse emissions between 27 MHz and 6 GHz, it is essential to calculate, at each measurement location, the Total Exposure Ratio (TER) [17], using the following relationship

$$\mathrm{TER} = \sum_{i>27\ MHz}^{6000\ MHz} \left(\frac{\overline{E}_i}{E_{\mathrm{lim},i}} \right)^2 \leq 1\ , \quad f \geq 100\ kHz \tag{4}$$

where $E_{\mathrm{lim},i}$ is the field strength limit for the related i-th sub-band, according to the imposed legislation (see also Table I). The enforced limits are not compromised if TER is lower than 1 [17].

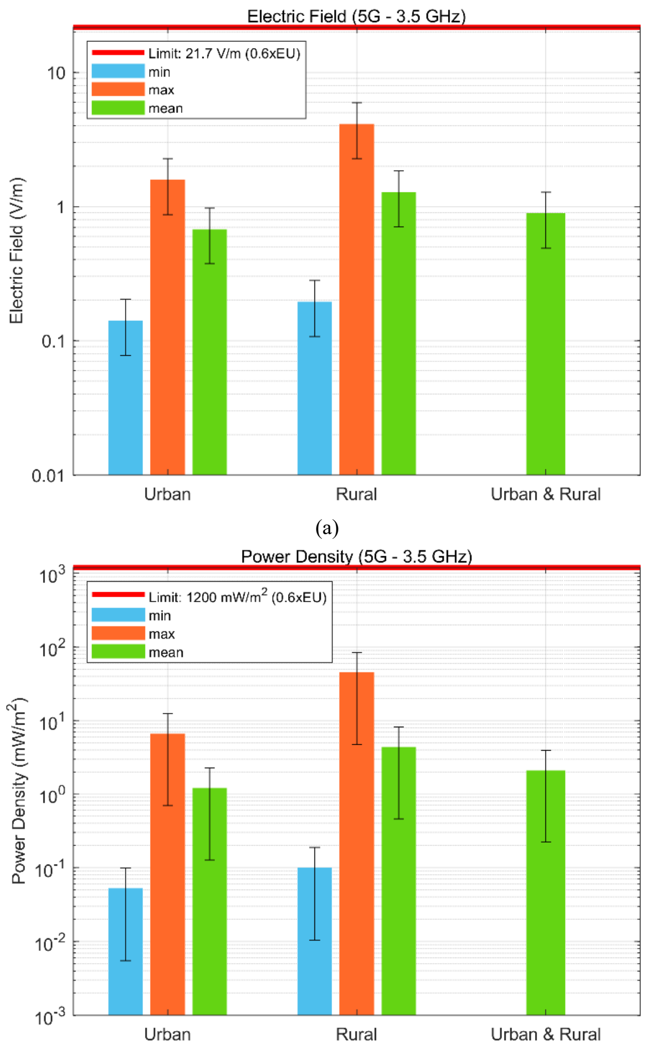
III. ENFORCED LEGISLATION AND LIMITS

In 1998, on the basis of diverse research studies and measurements, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) issued suitable regulations for the protection of the general public and occupational exposure [17]. The specific rules have been legislated by the European Union (EU) in the context of directive 1999/519/EC [18] and each member state has incorporated those regulations in their legislation. In 2020, ICNIRP issued updated and amended regulations, where for the whole-body exposure the imposed limits remain the same, provided an averaging over a 30-min period [19]. However, the specific guidelines, are not yet followed by the EU, and in turn by each member state. Therefore, the initial ICNRIP regulations (1998) are still in force. Greece (GR) has also embraced EU and ICNIRP-98 regulations [20]. However, Greece has imposed two supplementary reduction factors for the general public, selecting limits being 0.7 and 0.6 of those of EU [21]. The second reduction factor is employed when sensitive facilities (e.g., hospitals, schools, kindergartens, daily care) are located within a radius of 300 m from an operating antenna. It should be pointed out that these factors are applied on the power density limits, but one can easily resolve the relative electric field limits applying (2).

The relative enforced limits in EU and Greece for different frequency zones, in terms of electric field and power density values, are summarized in Table I. In the case of broadband recordings, which include the entire frequency range of 27 MHz - 6 GHz, the exposure values are compared with the stringent limits, thus considering the worst-case scenario. According to Table I, these values are 21.7 V/m and 1.2 W/m^2, for the electric field and power density, respectively. Finally, in terms of TER, the protection bound is 1, incorporating the expanded uncertainty as specified in [10].

IV. EXPOSURE RESULTS AND DISCUSSION

The exposure results, exclusively from 5G antennas, are presented in Fig. 1 for urban and suburban locations. The parameters are calculated applying (1) and (2), for the specific frequency sub-band at 3.5 GHz. The error bars indicate the expanded uncertainty, selected 44.7% at this frequency. The exposure parameters are compared with the most stringent Greek limits (0.6×EU), as a worst-case scenario.



(a)

(b)

Fig. 1. Exposure parameters from 5G (3.5 GHz) base stations in urban and rural locations. (a) Electric Field. (b) Power Density. The error bars indicate the uxpanded uncertainty.

In urban areas the measured electric field varies from 0.14 V/m up to 1.57 V/m, with an average value of 0.67 V/m. In respect, rural locations exhibit higher levels, being in the range of 0.19-4.10 V/m, with an average electric field of 1.27 V/m. Similar results are obtained in terms of power density, where rural locations demonstrate higher levels.

The inherent operation of the cellular network architecture justifies this difference, since rural locations necessitate extended coverage that entails high-power transmit antennas. This is also required to compensate excess path loss at 3.5 GHz. On the contrary, urban areas with very high user densities employ very small cells, thus requiring low-power transmissions to overcome interference. The cell densification, which is the cornerstone of the 5G network structure [1], accounts for the lower exposure levels in urban areas. In any case, the exposure results, incorporating the expanded uncertainty, do not exceed the legislated limits, as one can observe in Fig. 1.

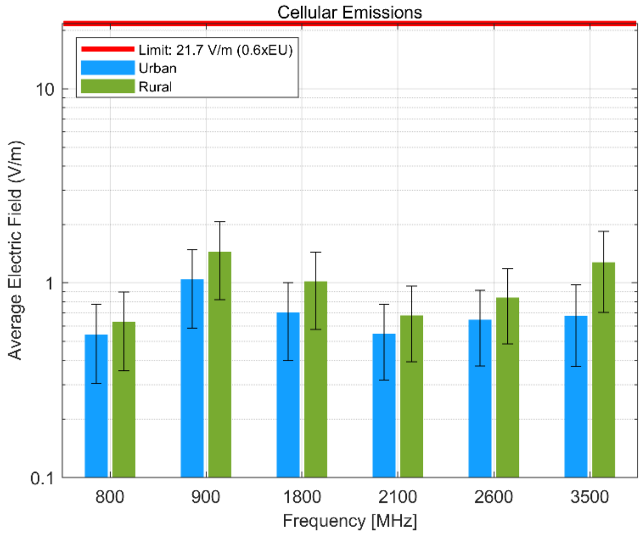


Fig. 2. Cellular emissions in terms of electric field, in every recorded frequency band. The error bars indicate the uxpanded uncertainty.

Combining all the measured locations (urban and rural), their average power density (2.09 mW/m^2) is about 0.17% of the strictest Greek limit (0.6×EU) and 0.02% of the EU/ICNIRP98 limits.

Moreover, the maximum power density (44.6 mW/m^2) was observed in rural areas and corresponds to 4.5% of the worst-case limit in Greece (0.6×EU), and about 0.4% of the EU/INCRIRP98 limits. The measured values are on the same order of magnitude with those found in [5], [6], and [8], and slightly higher than those reported in [4], yet the latter measurements took place explicitly in cities (i.e., urban environment).

Exploiting the frequency selective capability of the measurement equipment, it is of interest to compare the emissions from 5G antennas with those detected in other frequency bands. All these are collocated in the same base station, as mentioned previously. Fig. 2 presents the averaged electric field values in urban and rural areas in each recorded frequency band for cellular services. The results verify the difference between urban and rural emissions, where the latter remain higher in every frequency band. The exposure values from 5G antennas are comparable with those at 1800 and 2600 MHz, especially in urban locations (0.64-0.69 V/m). Another interesting observation is that rural areas demonstrate increased exposure levels at 3.5 GHz compared with other cellular emissions, except 900 MHz. This occurs due to the excess path loss that the planners have to overcome at 3.5 GHz, thus increasing the transmission levels. On the other hand, 900 MHz cells operate ancillary, overlaying rural areas, and cover extended regions that also mandates higher power levels. Finally, considering independently each cellular frequency band ($\bar{E}_i$), the electric field, including the uncertainty, is found below 2.5 V/m, being many times lower than the adopted limits, as one can observe in Fig. 2.

TABLE II. STATISTICAL PROPERTIES OF THE EXPOSURE PARAMETERS.

		E_{total} [V/m]	S_{total} [mW/m^2]	TER×10^{-3}
Urban	***Min***	0.76 ± 0.34	1.52 ± 1.36	0.39 ± 0.16
	Max	3.77 ± 1.68	37.62 ± 33.63	10.26 ± 5.48
	Mean	1.88 ± 0.84	10.57 ± 9.45	2.84 ± 1.41
	Median	1.71 ± 0.76	7.77 ± 6.94	2.15 ± 1.00
Rural	***Min***	0.43 ± 0.19	0.52 ± 0.46	0.13 ± 0.05
	Max	6.97 ± 3.11	129.11 ± 115.42	27.71 ± 12.06
	Mean	2.68 ± 1.20	30.11 ± 26.92	7.58 ± 3.88
	Median	1.85 ± 0.83	9.09 ± 8.12	2.25 ± 1.12

Then, applying (3), the measured E_{total} is calculated (K = 17) taking into account all the emitting sources between 27 and 6000 MHz. Accordingly, the total power density is calculated by $S_{total} = (E_{total})^2/377$, and TER using (4). The analytical statistics of those parameters are listed in Table II, for urban and rural environments. It is worth mentioning that the expanded uncertainties for E_{total} and S_{total} are yielded considering the maximum measured expanded ambiguity (44.7%), whereas TER is obtained considering the strictest Greek limits.

According to Table II, it is evident that all the emissions (including their maximum uncertainty) are well below the enforced limits. The highest recorded power density, adding the uncertainty, is found 244.5 mW/m^2, which appears in rural locations. This value corresponds to about 20% of the most stringent Greek limit and 2.4% of the EU/ICNIRP98 limits. Finally, the maximum value of TER is found in the range of (27.71±12.06)·10^{-3}. Including the ambiguity, this value is lower than 1, thus indicating no limit violation. It corresponds to about 25 times below the strictest Greek limits.

Furthermore, it is important to assess how each emission source (from each recorded sub-band) affects the TER. More specifically, the proportional contribution C_i (%) from each i-th frequency sub-band, between 27 and 6000 MHz, can be calculated by

$$C_i = \left[\left(\frac{\bar{E}_i}{E_{\lim,i}} \right)^2 \Big/ \sum_{i=1}^{K} \left(\frac{\bar{E}_i}{E_{\lim,i}} \right)^2 \right] \times 100 \qquad (5)$$

where $\bar{E}_i$ is the spatially-averaged electric field given by (1) with K = 17, and $E_{\lim,i}$ is the field strength limit for the related i-th sub-band (see Table I). The outcome is yielded averaging urban and rural data. The results are provided in Fig. 3, where it is evident that, apart from the cellular emissions, the contribution of the rest of the services is negligible and below 2.5%. The contribution solely from 5G emissions is about 12%, whereas GSM-900 services demonstrate the highest contribution toy TER (40%).

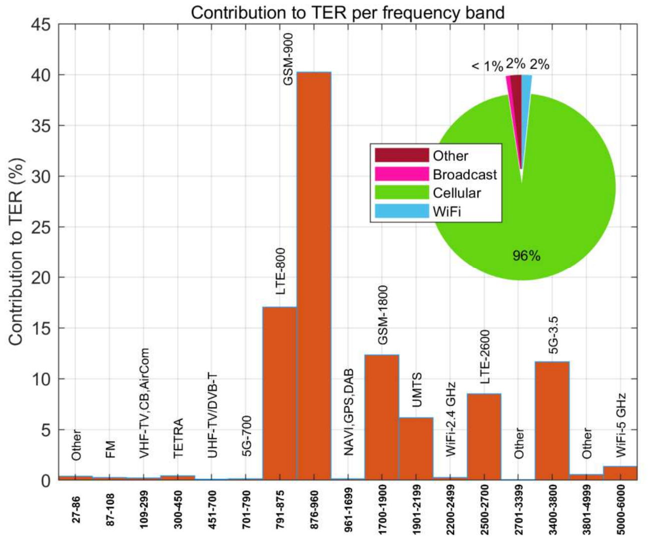


Fig. 3. Proportional contribution to TER from each frequency zone between 27 and 6000 MHz. The corresponding service is also indicated. The outcome is obtained averaging urban and rural data.

The superimposed pie chart provides a more representative perspective of the most essential emissions. Aggregating the emissions from all the cellular services their contribution reaches up to 96%.

On the other hand, all the broadcast services (e.g., FM, VHF-TV, UHF-TV, and DVB-T) exhibit a minor contribution, lower than 1%. However, this is expected, since the recordings took place at locations far away from antenna parks, or other individual broadcast antennas. Furthermore, WiFi emissions (at 2.4 or 5 GHz) contribute about 2% to TER, and that because the measurements included locations near premises, residences, or stores with operational WiFi radios. Finally, all the rest of the recorded services (Other) account for the 2% of the total exposure levels.

V. CONCLUSION

This paper presented preliminary results of RF-EMF measurements in outdoor environment. The purpose was to assess the exposure levels from 5G antennas and compare its emissions with other existing services. Frequency selective measurements were performed in various urban and rural locations between 27 MHz and 6 GHz. The measurement results revealed that 5G emissions are higher in rural than in urban locations, which is attributed to the innate architecture of the 5G networks. The maximum recorded power density from 5G services (44.6 mW/m^2) occurred in rural areas and corresponds to about 0.4% of the European Unions' legislated limits. Finally, emissions explicitly from 5G services contribute about 12% to the total exposure levels, whereas the contribution of all the cellular services reaches 96%.

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