Electromagnetic radiation exposure of multioperator co-sited urban base stations

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Abstract: Mobile network operators (MNOs) concurrently use different generations of wireless technologies. The base stations (BSs) of different technology generations are co-located in order to decrease operational costs. Furthermore, the MNOs cooperate in order to co-site their base stations. Such an urban site includes more than 25 actively radiating antennas on average with different frequencies and modulations. Electromagnetic radiation (EMR) measurements performed in such an environment may have reduced accuracy. In this paper, the authors propose a new approach for the measurement of EMR in multiple mobile technology interwoven urban BS sites, where more than one operator exists. The maintenance activities are also investigated with their frequency of occurrence and their duration for EMR exposure assessment and the statistics are reported for the first time in academia. On sampling the signal strength and radiation in different positions for the tested urban sites, electrical field strengths as high as 90 V/m were observed. The results are classified according to frequency bands and possible technologies. The probable bioelectromagnetic effects of such EMR exposure on maintenance workers are discussed with the provision of statistical data of co-located BSs and their maintenance activities. A new occupational EMR exposure risk assessment approach is proposed by taking into consideration the massive multiinput multioutput (MIMO) antenna technology.

Key words: Base station, 5G, 4G, electromagnetic radiation, mobile communication, massive MIMO

1. Introduction

From the second generation (2G) macrocell, minicell, and microcell structures, mobile networks evolved into a structure where technologies using a wider spectrum such as third generation (3G) wide-band code division multiple access (WCDMA) and long-term evolution (LTE – fourth generation (4G) and beyond) orthogonal frequency division multiple multiplexing (OFDM) are used. These latter technologies benefit from picocell and femtocell architectures, and additionally offloading onto other wireless technologies such as Wi-Fi [1].

A mobile network operator (MNO) moves on to the next technology, which has better spectrum efficiencies and reduced operational expenditures, while still complying with the regulatory requirements for the service continuation of existing technologies [2]. Therefore, many of the existing mobile radio networks (MRNs) are multiple technology interwoven complex structures [2].

The radio base stations (BSs) of different technologies are generally co-located in order to share cooling, cabling, power, and transmission substructures. This co-locating strategy increases the number of concurrently radiating antennas per urban BS site. On the other hand, there is a certain public and regulatory pressure on how the antennas and the BSs should be installed in urban areas [2]. Thus, MNOs have started using combo

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antennas, which encapsulate multiple antennas for different frequency bands within a single radome, in order to minimize public concerns (Figure 1).

Figure 1. An urban multioperator site.

Combo antennas may cover different combinations of cross-polarized pairs and support a diverse number of technologies at the same time: as an example, 900 MHz 2G, 1800 MHz 3G, and 2600 MHz 4G. They come in cross-polarized antenna pairs of 2 to 5 and can support the entire mobile spectrum since each cross-polarized pair is technically independent from the rest. As for the limitations, the increased size negatively affects the wind and ice load limitations. The increased weight, on the other hand, puts more pressure on antenna poles and fixings. Having all antennas within a single radome may elevate temperatures and may affect the performance, too. Last but not least, packing the antennas too close to each other may trigger electromagnetic near-field effects, causing degradation in antenna performances, especially in the uplink direction.

As a result, the whole urban environment is intentionally or unintentionally exposed to electromagnetic radiation (EMR) at different levels. This exposure raises concerns and questions about the impact of the EMR on human health and life. A number of papers were devoted to the issue of bioelectromagnetic effects [3–15]. These include cellular, immunological, hematological, auditory level responses to EMR exposure such as heat shock protein secretions, protein leakages, cellular ion channel anomalies, blood sugar level fluctuations, and hearing loss, as well as cognitive function degradations.

Certain measurements of EMR have to be done in order to define such bioelectromagnetic effects. The aim of this paper is to discuss how these EMR measurements in a complex multitechnology co-sited BS environment should be done, and to foresee probable bioelectromagnetic effects of such EMR exposure on maintenance workers and propose a new standard of occupational exposure risk for them.

The rest of the paper is organized as follows: Section 2 describes EM radiation metrology with its fundamental issues; Section 3 presents governed methods and performed measurements; Section 4 provides a brief discussion of the results, a classification of sites, and the proposed combined risk factor; and, finally, Section 5 provides our conclusions.

2. EM radiation metrology

EMR is not detectable via organoleptic tests, which means that its detection, as well as any associated work, research, and measurements, require the use of various tools. EMR metrology is extremely important because
it is a necessary requirement for activities related to the electromagnetic environment and thus the protection of the population from the effects of EMR [16].

2.1. Finding the border between the near and the far field

In order to distinguish various measurement options, metrologists working with electromagnetic waves (EMWs) have divided them into three zones: near, far, and intermediate. The division is symbolic since there is no strictly defined discontinuous boundary between them [9]. The boundary between the near and far zones can be determined on the basis of a simple relation by Eq. (1) [16–20]:

\[ r \geq \frac{2D^2}{\lambda}, \]

where \( r \) is the boundary between zones near and far, \( D \) is the largest dimension of the antenna, and \( \lambda \) is the wavelength.

Described here are the traditional definitions to distinguish the specific measurements in the near and far zones. In the authors’ opinion, the near field exists wherever we perform measurements. This is the result of comprehensive experience and applies to measurements in urban BS sites, where there may be multipath propagation, as well as interference and reflections [16–19]. There is a need for caution, even when measuring in the far field, where the directional antennas may “fail to capture” all sent rays.

2.2. EMR measurement accuracy

One of the greatest problems in EMR metrology is the accuracy of measurements. Model EM waves (waves with known parameters) are being used to calibrate gauges and test equipment and body sensitivity to EMR [16–18]. As mentioned before, EMR measurements are among the least accurate measurements when compared to other physical quantities [9].

The first factor that influences the accuracy of the measurement is the error of creating a model EMW, which is between 5% and 10% [18]. Detailed accuracy analysis of a model EMW performed with dipole, frame, and tube antennas, as well as model transverse electromagnetics (TEM), can be found in the literature [16, 17, 20, 21].

The second factor, which has a big influence on the measurement’s accuracy, is called the human factor. It is basically an error that is made by the person performing the measurement. Different people performing measurements will get different results [18]. Therefore, the human factor contributes to a large error, but unfortunately it is not under consideration when drawing up results. One should also keep in mind that the person performing the measurements may affect the measurement by his very existence introducing capacitive and reflective effects or resonating the field in the measurement environment.

Finally, the person conducting the measurement is an obstacle for the EMWs in uplink and downlink directions. Every generation of mobile telecommunications technology has a dynamic power control feature. Thus, conducting a measurement may increase the power output of the wireless antennas and, in return, may affect the results a second time.

2.3. Bioelectromagnetic effects

The effects of EMWs on the human body are twofold: thermal and nonthermal. The thermal impact is caused by the rising of the temperature of tissues and body fluids. It results in pathological changes and physiological
responses. The increase in frequency causes an increase in the threshold current density. It also raises the
intensity of energy absorption and causes thermal effects at frequencies above 10 MHz. The temperature
rise depends on many factors, such as power density, frequency, and individual characteristics of the person
undergoing the exposure [18, 22]. For example, an increase in frequency also increases the energy of the
electromagnetic wave.

When there are changes observed in the body without raising the temperature of the tissues, the
nonthermal effect may be the reason. This effect plays a primary role at low frequencies of 100 kHz and
less, where the absorption of electromagnetic energy by the body is unnoticeable.

In the case of mobile systems, mainly thermal effects are observed and analyzed. To calculate the energy
absorbency, specific absorption rate (SAR) is used. In experiments, the following formula of Eq. (2) is used
[22, 23]:

\[
SAR = \frac{c_w \Delta T}{t},
\]

where \( c_w \) is specific heat, \( \Delta T \) is temperature rise, and \( t \) is time of exposure to EMR.

For numerical purposes, a better definition of SAR is as follows:

\[
SAR = \frac{\sigma E^2}{\rho},
\]

where \( E \) is the electrical field norm, \( \sigma \) is the sample’s electrical conductivity, and \( \rho \) is the sample’s density.
SAR is usually calculated based on peak, local peak, or average values over the average of 1 or 10 g of tissue.

3. Methods and measurements

There are three MNOs in Turkey. These MNOs provide service in 2G, 3G, and 4G at the same time. All
operators may use 800 MHz 3G and 4G, 900 MHz 2G and 4G, 1800 MHz 4G, or 2100 MHz 3G and 4G as a
possibility, and 2600 MHz 4G. The differences are in the bandwidth allocations. Three urban sites were selected
for the measurements, where all three operators were active in all three generations of technology. In each site,
multiple measurements were taken accordingly.

The active bands were classified per technology and a cumulative electric field value was recorded. All
measurements were performed preferably 3 m away from the antennas’ front or 1 m away from the antennas’
back, and the local maxima were recorded. Horizontal samplings were also done for the same positions in order
to gain some insight on the electrical tilts and reflections as shown in Figure 2. These horizontal samplings
helped detect electrical tilts and provided an understanding of EM hot spots. Samplings over the antenna central axis were not necessary, because only mechanical tilts might have created a higher EM field above the axis and mechanical tilts could readily be detected by human eye.

All measurements were performed during midday hours on weekdays other than Monday and Friday in order to have reasonable mobile traffic load on the antennas.

Two types of measurement devices were chosen: the Narda SRM-3006 | 9 KHz-6 GHz Spectrum Analyzer with 3-Axis 27 MHz-3 GHz E-field antenna and the Narda NBM-520 | 100 KHz-6 GHz with EF0391 probe. The spectrum analyzer observations were utilized to detect the active spectrum, while the probe-based measurements were utilized to measure the E-field strength in V/m.

The antennas are colored according to their technology. All antennas of a designated color point outward from their pole base, which is represented with a circle, or to the nearest roof edge.

In the first location, the active bands were observed as 800, 900, 1800, and 2100 MHz (Figure 3). The measurements were in between 30 and 56 V/m (Figure 4). The roof-top had an elevation near the exit, where the two main antenna clusters were located. The frequency bands were assigned agnostic to the technology, so operators might have been using any of the possible technologies such as 800 MHz - 3G/4G, 900 MHz - 2G, 1800 MHz - 2G/3G/4G, 2100 MHz - 3G/4G, or 2600 MHz - 4G.

In the second location, the same telecommunication frequencies were active as in the first location. There were also additional active bands probably due to air traffic control (international airport), marine (Bosphorus Strait) radars (both in-line-of-sight), and some possible domestic Wi-Fi (Figure 5). The measurements were in between 2.48 and 9.57 V/m (Figure 6), and were rather low compared to the first location. Instead of front measurements, back lobe measurements at 1 m from the antennas were taken (Figure 1). The roof in the second location was absolutely flat.

In the third location, the spectrum analyzer output was less distinct, while telecommunication frequencies in use were still observable. One reason for these indistinct figures might be the radio hub tower we saw to the south of the site, and there was a clear line-of-sight to that tower. There were also some Wi-Fi signals once again (Figure 7). The measurements were in between 9.8 and 31.5 V/m (Figure 8). A local maximum at 1 m distance from three closely placed antennas was sampled with a value of 90.7 V/m (Figure 8). The roof in the third location had two elevations: one in the center and three on the sides versus the roof-top.
4. Discussion of results

We have observed diverse differences in the roof tops. Some locations had three different elevations or inclinations. Spectrum analysis proved to be critically important in order to check the available radio signals, and the probe-based measurements provided us with the local maxima observations. The antennas had mechanical (on 2G only) or electrical tilts, but it was not easy to detect electrical tilt by measurements. Meanwhile, the probe-based measurement in close proximity was sufficient to detect whether the antenna irradiated or not.

In the first and the third locations, the Wi-Fi signals were unexpectedly too strong for domestic modem outputs. The MNOs utilized Wi-Fi in those locations. In the third location, we had a clear line-of-sight of a telecommunication radio hub tower in close proximity. The antennas in the third location were also covered with metal pieces on their backs, possibly to block the back lobe signal. This application could have created unexpected reflections in the whole antenna cluster.

In our measurement sites, the antennas were mounted on monopoles and multipoles. These poles
hosted between 3 and 15 antennas. Different operators’ poles were also located in close proximity. The telecommunication maintenance people work in such an antenna-dense environment for fault removal. These tasks require 5–40 min of dedicated work inside the antenna cluster. Therefore, it is also important to have the statistics of the roof-top works. To give an idea of possible EMR exposure, we acquired the MNOs’ typical fault removal statistics, as shown in the Table.

| Fault type          | Instance       | Maintenance duration |
|---------------------|----------------|----------------------|
| Antenna             | 0.1/site/year | 40 min               |
| Connector           | 20/site/year  | 5 min                |
| Feeder cable        | 2/site/year   | 40 min               |
| Remote radio unit (RRU) | 50/site/year | 20 min               |
| RRU power           | 0.3/site/year | 30 min               |
| Minor civil works   | 2/site/year   | 90 min               |
| Major civil works   | 1/site/year   | 180 min              |

Because of the regulatory pressure on radio network availability performance and the lack of will and coordination among MNOs, the roof-top maintenance activities are conducted while the other BSs continue their operations [17]. From our measurement samples, maintenance people could be exposed to electrical field strength far above 100 V/m on certain occasions. When the duration of the task is considered according to the Table, one can expect the aforementioned thermal effect of EMR on the human body and especially on the human eye [3, 5, 12]. If nonthermal effects will also be observed on top of the thermal effect, there may be elevated occupational risks for both health and safety.

In order to foresee possible thermal effects, we conducted a simulation with the Comsol (FNL License No. 17073372) SAR human head model with a continuous wave 100 V/m electrical field strength at 2.45 GHz at the maintenance person’s head boundary. The simulation result was an increase of 0.28°C skin temperature on average with a maximum SAR value of 10.35 W/kg over 1 g for an exposure duration of 15 min. Comsol uses the Pennes’ bioheat transfer function for these calculations. In the microwave region that most of the latter mobile technologies use for service, the thermal wave model of bioheat transfer (TWMBT) can also be used, since this model provides a more realistic function [9]. Both models provide similar results for longer durations of exposure, as in our case.

There are some academic studies with similar measurements focused on public EMR exposure in urban areas [19, 25–29]. In some cases, the researchers focused on urban areas such as roads, living quarters, or public transportation. In such cases, the EMR was effectively caused by both uplink and downlink mobile communication radio frequency (RF) signals [25–29]. Some of these works included fixed measurement devices with periodic samplings [25, 26, 29], whereas in others, the samples were collected randomly or by drive tests for a brief period of time [27, 28]. These studies confirmed an increasing ambient EMR in urban zones, but they were not able to address the EMR issues in the immediate vicinity of base stations. There is no prior research on the roof-top immediate vicinity antenna measurements in both front and back lobe directions. The closest research studies we came across were done by Baltrėnas et al. and Haipeng et al. [19, 28]. Baltrėnas et al. measured front lobe radiation with an empirical antenna far-field distance deduction from the density of flux measurement changes as 15 m [19]. In the latter study, Haipeng et al. stated that the limiting value of a base station’s EMR must be regulated by taking into consideration the frequency, distance, main and minor lobe...
ranges, surroundings, tilt angle, and time of relevant factors like co-site [28]. These are useful interpretations of the problem, but we can still expand it further.

Our roof-top measurements at all three sites were done within a range of 15 m antenna to antenna span and we were always in the near field according to Baltrėnas et al. [19]. Secondly, we made front and back lobe power measurements, and we sometimes observed high readings even for back lobe EMR. Our front lobe measurements at 3 m distance were in the range of 11–90 V/m with an average of 35 V/m compared to 52 V/m for the single antenna measurements of Baltrėnas et al. [19]. The measurements were taken 2 months after the initial launch of 4G service. It is safe to say that the 4G network usage, which has increased 15-fold as of November 2018, was not common then. With the electrical tilt effects and the spread of antenna clusters in different locations of the roof-tops, it was almost impossible to foresee EMR by simulations. We should also note that electrical tilt is also a dynamic feature of the radio network controllers, and it can change in a matter of seconds depending on the MRN traffic load and demand [1, 2].

It would be useful to classify the roof-top multitechnology co-sited urban BSs with certain criteria. First of all, we would like to put the antenna spread as the first and foremost criterion. We have observed the following spreads: side-spread, concentrated cluster, and randomly spread. MNOs prefer to use side-spread for better power utilization of their antennas with better back lobe isolation [2]. If there is not enough room on the roof-top, then MNOs tend to use concentrated clusters. Lastly, the random cluster also appears, probably due to lack of coordination of MNOs using the same roof-top by arriving in different time periods. They thus locate their antennas within the existing limitations on the roof-top.

The second criterion is the number of elevations of the roof. Most of the roofs have a single elevation/are flat, or inclined, or have two levels. In general, single elevation roofs are good for side-spread antennas, inclined roofs are good for randomly spread antennas, and two level elevations are good for concentrated antenna clusters.

The final criterion we offer is the number of combo antennas per site. The combo antennas radiate three or four beams at the same time in different frequency bands. As we have observed in concentrated clusters, the antennas are in close proximity, and maintenance workers may be subject to such exposure from two or more combo antenna front beams at the same time.

We can now propose the occupational exposure risk for maintenance people based on these criteria:

\[ XR = E \times C \times S \times ET, \]  

where XR is the increased occupational risk factor, E is the elevation risk coefficient (flat = 1; two elevations = 4; three or more elevations = 2), C is the combo antenna risk coefficient ((average combo antenna ratio per site + (1 - avg. combo antenna ratio per site)) \times 3), S is the antenna spread risk coefficient (side-spread = 1; concentrated antenna cluster = 10; rand. spread antennas = 3), and ET is exposure time risk ((1 + ratio of co-sited base station ratio in maintenance area) \times (no. of co-sited base station ratio in maintenance area / 50)).

In the calculation of XR, we had the following assumptions from our field observations. Two elevations mean that the maintenance must be done in front of the front lobe of other antennas. As the number of elevations increases, the risk decreases since there will be screening effects. Combo antennas have a multirod concurrent radiation risk, and we took the average number of rods per combo antenna as 3. Antenna spread risk is the most important factor. Concentrated clusters as in the third measurement site pose a serious threat. Finally, the exposure time risk is calculated over multioperator multitechnology co-sited location value per maintenance area. The maintenance teams' responsibility areas included 50 such sites on average among 3 MNOs. Thus, we have assumed 50 to be the nominal occupational base value.
EMR metrology is equally important because it is a sine qua non condition of the measurement activities of the electromagnetic environment, as well as of academic research, especially research on EMR effects on living organism and in particular on human beings. Therefore, the determination of protective regulations is related to EMR metrology, both from the safety perspective of work as well as from the protection perspective of the population. Nonetheless, EMR measurement inaccuracy is not taken into account in protection standards [16]. EMR metrology’s achievable accuracy for the far field is about 1 dB; in the near field, it is about 3 dB, ranging up to 6 dB in certain scenarios [10].

5. Conclusions

Our aim was to provide some insight for researchers working on the epidemiological and biological effects of the electromagnetic fields emitted by multioperator co-sited urban base stations. The base station EMR measurements are prone to the effects of fluctuations by active traffic/measurement time, antenna type, antenna tilt, antenna cluster density, and structure of the roof-top, as well as other external factors. A broadband probe-based measurement with vertical samplings may provide more insight into the EMR power density, while when utilized together with a spectrum analyzer the output data become much more meaningful.

Telecommunications maintenance people are subject to electric field values over 100 V/m in the case of concentrated antenna cluster co-sites. Taking into consideration the new launch of 4G services at the time of the measurements, these values may easily increase twofold or threefold with exposure from two combo antennas as in the case of the third measurement site. In rare but probable cases of fault removal activities such as antenna replacement as in the Table, there can be elevated SAR values in the heads and torsos of the maintenance people. In general, maintenance people will be exposed to base station EMR for about 2.5 h per day based on 50 sites per responsibility area. The immediate effects [3, 4, 12] and long-term effects [8] are available in academic studies. Recent studies showed much more subtle effects [12–15]. Such high EMR values as observed in this study were not even considered in any of those studies.

Taking into consideration the measurement values and the EMR metrology ambiguity, one may have serious concerns about maintenance people’s health in light of recent studies [12–15]. Since the current urban percentage of co-sited BSs is 60% for three MNOs and 24% for two MNOs [17], precautionary and regulatory steps should be taken in order to mitigate such occupational risks in these multioperator co-sited BSs. Therefore, a regulation taking into consideration the increased occupational risk factor (XR) may prove to be useful to avoid overly concentrated clusters.

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References

[1] Mukherjee S. Analytical Modeling of Heterogeneous Cellular Networks. New York, NY, USA: Cambridge University Press, 2014.

[2] Uluaydin NK, Seker SS, Citkaya AY. Application of EM broadband backlobe absorber for antennas. In: Applied Computational Electromagnetics, 2015 31st International Review of Progress; Williamsburg, VA, USA; 2015. pp. 1-2.
[3] Schmid G, Neubauer G, Mazal PR. Dielectric properties of human brain tissue measured less than 10 h postmortem at frequencies from 800 to 2450 MHz. Bioelectromagnetics 2003; 24 (6): 423-430.

[4] Ibele BL, Roth CC, Ledwig PB, Payne JA, Amato AL et al. Cellular effects of acute exposure to high peak power microwave systems: morphology and toxicity. Bioelectromagnetics 2016; 37 (3): 141-151.

[5] Calvente I, Pérez-Lobato R, Núñez MI, Ramos R, Guxens M et al. Does exposure to environmental radiofrequency electromagnetic fields cause cognitive and behavioral effects in 10-year-old boys? Bioelectromagnetics 2016; 37 (1): 25-36.

[6] Wushech H, von Heln U, Mikus E, Funk RH. Effects of PEMF on patients with osteoarthritis: results of a prospective, placebo-controlled, double-blind study. Bioelectromagnetics 2015; 36 (8): 576-585.

[7] Varsier N, Plets D, Corre Y, Vermeeren G, Joseph W et al. A novel method to assess human population exposure induced by a wireless cellular network. Bioelectromagnetics 2015; 36 (6): 451-463.

[8] Meo SA, Alsubaie Y, Almubarak Z, Almutawa H, Al Qasem Y et al. Association of exposure to radio-frequency electromagnetic field radiation (RF-EMFR) generated by mobile phone base stations with glycated hemoglobin (HbA1c) and risk of type 2 diabetes mellitus. International Journal of Environmental Research and Public Health 2015; 12 (11): 14519-14528.

[9] Özen Ş, Helhel S, Çerezci O. Heat analysis of biological tissue exposed to microwave by using thermal wave model of bio-heat transfer. Burns 2008; 34 (1): 45-49.

[10] Özen Ş, Helhel S, Çolak H. Electromagnetic field measurements of radio transmitters in urban area and exposure analysis. Microwaves and Optical Technology Letters 2007; 49 (7): 1572-1578.

[11] Özen Ş, Helhel S, Bilgin S. Temperature and burn injury prediction of human skin exposed to microwaves: a model analysis. Radiation and Environmental Biophysics 2011; 50 (3): 483-489.

[12] Atilgan E, Coskun O, Comlekci S. Experimental finding of temperature rise and SAR values created by 900 MHz-1800 MHz-2450 MHz electromagnetic radiation on human brain tissue. Optoelectronics and Advanced Materials 2015; 9 (9-10): 1224-1229.

[13] Taheri M, Roshanaei G, Ghaffari J, Rahimnejad S, Khosroshahi BN et al. The effect of base transceiver station waves on some immunological and hematological factors in exposed persons. Human Antibodies 2017; 25 (1-2): 31-37.

[14] Das S, Chakraborty S, Mahanta B. A study on the effect of prolonged mobile phone use on pure tone audiometry thresholds of medical students of Sikkim. Journal of Postgraduate Medicine 2017; 63 (4): 221.

[15] Buckus R, Strukčinskiené B, Raistenskis J, Stukas R, Sildauskiéné A et al. A technical approach to the evaluation of radiofrequency radiation emissions from mobile telephony base stations. International Journal of Environmental Research and Public Health 2017; 14 (3): 244.

[16] Grudzinski E, Trzaska H. Electromagnetic Field Standards and Exposure Systems. Edison, NJ, USA: SciTech Publishing, 2014.

[17] Dlugosz T, Trzaska H. Proximity effects in the near-field EMF metrology. IEEE Transactions on Instrumentation and Measurement 2009; 58 (3): 626.

[18] Dlugosz T, Trzaska H. How to measure in the near field and in the far field. Communications and Network 2010; 2 (1): 65.

[19] Błatências P, Buckus R. Measurements and analysis of the electromagnetic fields of mobile communication antennas. Measurement 2013; 46 (10): 3942-3949.

[20] Grudzinski E, Trzaska H. EMF probes calibration in a waveguide. IEEE Transactions on Instrumentation and Measurement 2001; 50 (5): 1244-1247.

[21] Trzaska H. Primary and secondary EMF standards. In: Environmental Electromagnetics, The IEEE 2006 4th Asia-Pacific Conference; Dalian, China; 2006. pp. 769-770.
[22] Długoś T. Bioelectromagnetic effects measurements–SAR and induced current. Bio-Medical Materials and Engineering 2015; 25 (1): 1-7.

[23] Directive 2004/40/EC of European Parliament and of Council of the Minimum Health and Safety Requirements Regarding the Exposure of Workers to the Risks Arising from Physical Agents (Electromagnetic Fields) (18th Individual Directive within the Meaning of Article 16(1) of Directive 89/391/EEC), OJ. Nr. L-184, 2004.

[24] Turkish Regulatory Agency. Electronic Communications Law, No: 5809, 2008.

[25] Urbinello D, Joseph W, Verloock L, Martens L, Röösli M. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environmental Research 2014; 134: 134-142.

[26] Urbinello D, Huss A, Beekhuizen J, Vermeulen R, Röösli M. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Science of the Total Environment 2014; 468: 1028-1033.

[27] Cansiz M, Abbasov T, Kurt MB, Celik AR. Mobile measurement of radiofrequency electromagnetic field exposure level and statistical analysis. Measurement 2016; 86: 159-164.

[28] Haipeng Z, Zheng Q. Test for electromagnetic environment of mobile communication base station. In: Electromagnetic Compatibility, IEEE 2016 Asia-Pacific International Symposium; Shenzhen, China; 2016. pp. 1164-1167.

[29] Karadağ T, Yüceer M, Abbasov T. A large-scale measurement, analysis and modelling of electromagnetic radiation levels in the vicinity of GSM/UMTS base stations in an urban area. Radiation Protection Dosimetry 2015; 168 (1): 134-147.