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EVALUATION OF THE EM FIELD EXPOSURE IN THE RANGE OF 4G FREQUENCIES IN THE LABORATORY ENVIRONMENT

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Abstract. The aim of paper is to estimate the electromagnetic (EM) field radiation on the human body in the range of 4G operations. The analytical approach consists of application of concept of the equivalent cylindrical monopole antenna presenting grounded standing human. The analytical formulas, allowing to determine the EM field exposure are derived. The experimental setup, consisting of the spectrum analyzer USB-SA44B supplemented by the respective software, notebook for analysis of signals, transmitting-receiving antenna array designed of four microstrip antennas, the transmitting antenna operating in the frequencies 0.9 GHz, 1.8 GHz and 2.45 GHz, and signal generator SA6 are used for the measurements. The designed setup demonstrates the possibility to extract the spectral characteristics of radiation in the range of 4G operations that will used subsequently for the comparison with the modeling data. It is observed that the fixed strength of radiation depends on the sources of radiation. The perspective of design is evaluation of the SAR at the laboratory environment.

Keywords: 4G radiation, transmitting-receiving antenna, spectrum analyzer, outside calibration, EM wave spectrum radiation, SAR

Introduction

The increasing use of electromagnetic (EM) fields for a wide spectrum of applications is one of the technological achievements nowadays. But the ratio of the possible harmful effects of EM fields is also growing in the human life. Exceeding total-body exposure to the radio-frequency (RF) EM fields results in the increasing the human body inside temperature. To handle this issue, the international standards [1] and guidelines [2] have been substantiated, which use the total-body averaged specific absorption rate (SAR) as a representative metric to quantify the temperature rise in the human body. The SAR is the quantity of the RF power absorbed by the human body averaged over the total body. Since it is not suitable to evaluate the SAR inside the human, the computational results are often used to associate the SAR with the quantities external measurable, such as the characteristics of the incident EM field.

One of such technological applications is the mobile telephony. Now, the mobile phones are the most used electronic devices in the usual human activity despite the valuable impact that they have been and now expressed on the possible risk for health. The estimation shows that this impact is increasing now exponentially. The above requires the comprehensive study of their impact on the users.

The close nearest of mobile phones to the head of users results in a high SAR of the EM fields of radiofrequency range comparably to other sources of the radiation of such kind [1].

The EM fields of the G4/G5 telephony can evoke effects on human organisms due to both the thermal and non-thermal effects. The definitive effects of the first type on the human body and the brain tissue have been extensively studied, and the impact limits were estimated [2] – [4], but the effects of the second type are studied to a lesser extent [5] – [7].

The effects of EM field impact have been evaluated on the basis of the different experimental models at the laboratory environment [8], [9], and by modeling for humans [10], [11]. Such effects invoke alterations in the intracellular signal pathways likely the ionic density and changes in the calcium ionic permeability [12], the growing cell excitability or evoking the cell response to the stresses [13]. The EM fields radiated by mobile phones cause influence on the usual brain physiology by changes of cortical excitability that modulates the activity of the neural networks regarding the EM field instability in humans [14]. The above confirms that the measuring the rate of EM Field in the indoor environment, where the users of mobile phones spend their main time, and study of the EM radiation impact on the human body is an actual problem.

In this paper, we analyze the different kind of the equipment that can be used for the measuring the EM field intensity and basing on the extracted data to evaluate the strength of EM radiation, including the SAR values.

Main Material Presentation

The Parameters Defining the EM Field Exposure

For evaluation of the exposure of EM field on the human body a series of parameters is applied for using. The most usually involved is the specific Absorption rate (SAR). This parameter characterizes the rate of energy absorbed by unit mass of human body and is measured in units of watt per kilogram (W/kg) [15]. In practice, SAR is averaged either over the whole body, or over a small part of its. SAR for the EM radiation can be determined by the value of electric field vector and material parameter of body, and it defines as

$$\mathrm{SAR} = \frac{1}{V} \int_{V/V_s} \frac{\sigma(\mathbf{r})\,|\mathbf{E}(\mathbf{r})|^2}{\rho(\mathbf{r})} d\mathbf{r}\,, \qquad (1)$$

where V/V_s is volume of body or its part only, σ (**r**) is the electrical conductivity of body, ρ (**r**) is body/sample density. Usually, SAR is used to measure the exposure to EM fields in range from 100 kHz to 10GHz (range of radio waves [5]. As a rule, SAR is used for measurement of power, which is absorbed from mobile phone or during build of magnetic resonance imaging (MRI).

The value of SAR depends too much on the geometry of the body or its parts that is exposed by radiofrequency (RF) energy, as well as on the location and form of the source of RF radiation. Therefore, the measures must be realized taking into account the specific of source, such as mobile phone or MRI device.

Another recipe of measuring the impact of the EM field radiation is whole-body averaged (WBA) SAR. This characteristic is applied when the far-field exposure is determined for the case of a grounded human body in the frequency of 1-150 MHz. Usually, a semi-analytic approach based on the theory of cylindrical antenna is applied in such a situation, and a human body is approached by a lossy cylindrical homogeneous monopole antenna. The progress of such investigation that focus on the antenna theory and similarity between a quarter-wave monopole antenna and a ground human body one can find in [16] – [18]. Later, this approach was extended for the estimation of the EM field exposure at the resonant frequencies [19] – [21].

The aim of this paper is to extend the approach based on the theory of cylindrical antenna theory for study of the impact of the EM field exposure in the frequency range of 1-150 MHz [22] to range of 4G frequencies, to build the experimental setup for the explore the impact of the EM field radiation in the above frequencies, as well as to compare the computational and experimental data.

The Currents Acting on the Human Body

We should estimate the currents, which are induced on the human body under action of the EM field radiation to estimate the EM field exposure. We consider here the action of vertically polarized plane wave. The induced axial currents and total dissipated power inside the body (cylinder) supplemented this power are important to evaluate the respective SAR.

We assume that a symmetric current density inside the equivalent cylindrical monopole antenna presenting grounded standing human induces by time-harmonic vertically polarized plane wave. Let the high of antenna is equal to l, its radius is equal to a, and body is characterized by complex conductivity σ_b. The total induced axial current inside the equivalent antenna is [16]

$$I_z = V_0^{\varepsilon} v(z) + U_0 u(z) , \tag{2}$$

where

$$V_0^{\varepsilon} = -I_{sc}(0)\frac{2Z_A Z_L}{2Z_A + Z_L} , \quad U_0 = \frac{E_0}{k_2} , \tag{3}$$

$$v(z) = \frac{2i\pi k_0}{\zeta_0 \gamma \Phi_{dR} \cos(\gamma h)} \sin\gamma(h - |z|) + T_U(\cos(\gamma z) - \cos(\gamma h)) + T_D(\cos(\frac{1}{2}k_0 z) - \cos(\frac{1}{2}k_0 h)), \tag{4}$$

$$u(z) = \frac{4i\pi}{\zeta_0}\left[H_U(\cos(\gamma z) - \cos(\gamma h)) + H_D(\cos(\frac{1}{2}k_0 z) - \cos(k_0 h))\right], \tag{5}$$

where E_0 (measured in Vm^{-1}) is the electric incident field at the surface of body (antenna), k_0 is the wave number of free space, $Z_A = 1/(2v(0))$ (measured in Ω)is the driving point impedance of the same cylinder if driven at the ground. $Z_L(\Omega)$ is the load impedance at the ground of cylinder, $I_{sc} = U_0 u(0)$ is the current at the ground if there no load, and ζ_0 is the impedance of free space. The specification of the coefficients T_U, T_D, H_U, H_D, and Ψ_{dR} one can find in [21]; they presents some integral formula, which can be calculated numerically. The imperfectly conducting characteristic of the equivalent cylindrical antenna is described by the complex propagation constant γ [22]

$$\gamma = k_0\sqrt{1 - i\frac{4\pi z_i}{k_0 \zeta_0 \Psi_{dR}}} , \tag{6}$$

where z_i (measured in Ωm^{-1}) is the surface impedance situated to unit length of cylinder, which defines as [16]

$$z_i = \frac{\kappa}{2\pi a \sigma_{\omega}^{*}} \frac{J_0(ka)}{J_1(ka)} = r_i + i x_i , \tag{7}$$

where $J_0(ka)$ and $J_1(ka)$ are the zeroth- and first-order function of Bessel, respectively. The coefficient κ has form

$$\kappa = \sqrt{-i\omega\varepsilon_0\mu_0(\frac{\sigma_{\omega}^{*}}{\varepsilon_0} - i\omega - \frac{4\pi z_i}{\mu_0 \Psi_{dR}})} , \tag{8}$$

where ω is the angular frequency, ε_0 and μ_0 are the permittivity and permeability of a free space, respectively.

We should have the value of the total average dissipated power P_{dis} inside the cylinder, for our situation it has form [18]

$$P_{dis} \simeq \frac{1}{2}\int_0^l r_i |I_z(z)|^2 dz , \tag{9}$$

where r_i is real part of z_i in (7). WBA SAR is characterized as the total average RF power, which is absorbed by the antenna (human body), divided on its total mass [23]. Following this rule, the total averaged absorbed power per unit mass is

$$WBA-SAR_{cyl} = \frac{P_{dis}}{W_c} = \frac{r_i}{2\pi\rho a^2 l}\int_0^l |I_z(z)|^2\, dz\,, \tag{10}$$

where ρ is density of body, weight $W_c = \pi\rho a^2 l$.

An equivalent cylindrical dipole antenna approaching the isolated human body is characterized by the parameters [22]

$$a = L_1\sqrt{\frac{W}{\pi\rho H}}\,,\quad h = H\,, \tag{11}$$

$$\sigma_\omega^* = L_2\frac{2x}{3-t}\sigma_{mus}^*\,, \tag{12}$$

$$\rho = L_3\frac{\rho_m}{t}\,, \tag{13}$$

where L_1, L_2 and L_3 are known constant, σ_{mus}^* is defined in accordance with [23], $\rho_m \approx 1050$kg/m^3 [24], variable t is function defining the lean-body-mass of the body [22]. The function t is given as

$$t = 0.321 + \frac{1}{W}(33.92H\text{-}29.53)\,, \tag{14}$$

for males, and

$$t = 0.295 + \frac{1}{W}(41.81H\text{-}43.29)\,, \tag{15}$$

for females.

Eqs. (14) and (15) testify that parameter x depends on the weight and high of human. If to consider the fixed frequency and parameters of body, one can conclude that value of $WBA-SAR_{cyl}$ in Eq. (10) depends on the three parameters L_1, L_2, L_3 [22]. These parameters can be used either as the optimization ones or they can be used for the validation of model when comparing with other approaches, as example, the FDTD-method, proposed in [24]. The other important role of these parameters is application to determination of the resonant frequencies providing the extrema of SAR [22].

Equipment for Measurement of EM Field

The equipment for measurement of EM field characteristics consists of receiving-transmitting antenna of pin type, allowing to operate in the range of frequencies 900 GHz, 1800 GHz, and 2450 GHz. The spectrum analyzer SA6 with the standard input impedance 50 Ohm, operating in the range up to 6GHz is considered as source of high-frequency radiation. The frequency range of built-in tracking generator is from 35 MHz up to 6.2 GHz that allow to evaluate the 4G/5G working frequency range. The noise floor is not less than -90 dBm that provide the visible difference between the active signals and noise, and the value of error attenuation is not greater than 8dB. The attractive frequency characteristics of device are the following: frequency range: from 1 Hz to 4.4 GHz (RF Preamp Off); 500 kHz to 4.4 GHz (RF Preamp On); internal frequency reference accuracy: ±1 ppm; counter accuracy: ± (1 Hz + time base error); resolution bandwidth: 0.1 Hz to 250 kHz and 5 MHz. The above parameters allow to curry out the measurement with accuracy sufficient to many practical applications. The receiving-transmitting antenna with the connected generator is shown in Fig. 1.

The receiving antenna array consisting of four microstrip antennas is used for getting the signals. It is connected with the spectrum analyzer by the standard 50 Ohm SMA RG316 RF cable, and the spectrum analyzer is connected with PC by USB 2.0 port. The setup for fixing the input radiation is shown in Fig. 2.

Fig. 1. The receiving-transmitting antenna with the generator SA6.

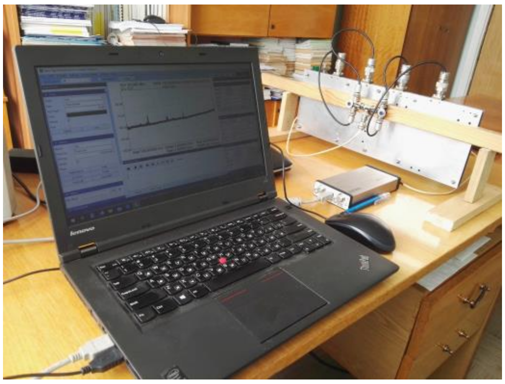

Fig. 2. The setup for measurement of the spectral EM field characteristics

The USB-SA44B Measurement Capabilities

The USB-SA44B provides carrying out a considerable range of the RF measurements, with the resolution bandwidths from 1 Hz up to 250 kHz. The existing internal I/Q demodulator collects about 2 Megabytes of the information per second, and a hardware-limited bandwidth is equal to 250 KHz. The ranges with spans greater than the above are as a rule a superposition of many smaller ranges, combined analytically to reject image and falsified responses.

The specific characteristics of device are:

- The spectrum analyzer USB-SA44B does not posses image rejection on the hardware-based implementation, instead of this, one is relying on the own software algorithm, which allow to reject the image responses. This algorithm combines the incoming RF signals with two separate local oscillator frequencies, which are spaced typically by 21.4 MHz and in the time diapason up to 100 milliseconds, and rejects responses which are not presented in both the ranges.
- The wide sweeps of the strong signals, mainly at the frequencies higher than 1 GHz, may be characterized by the noticeable fractional-N spurs. In order to eliminate these spurs, we should set our span up to 200 kHz or less. For such narrowband mode, the input signal is mixed by two not neighbor local oscillator frequencies with the different frac-N modulus parameters to two not neighbor but close frequencies, switch are that the fractional-N spurs are fully masked out.
- The spectrum analyzer USB-SA44B at each time can stream up to 250 kHz of spectrum to its internal software operating on the connected PC or laptop. The real-time mode demonstrates this data stream in the specified frequency domain.
- In the case of modulated signals, which do not exceed the value of 250 kHz bandwidth, the characteristics of time-domain amplitude, frequency, and phase data, as well as the several modulation measurements, are visible in the Zero Span mode.
- The switches of spectrum analyzer between two neighbor frequencies, four attenuator parameters, two settings of preamplifier, two frequencies of ADC clock, and three settings of IF gain, when the measuring signals and performing image suppression, are accessible. Unless one can disable explicitly the automatic settings, the optimal settings for the reference level, the central frequency, and span settings are automatically selected. One can simply select a reference level, which is a several dB greater than the level of the input signal.

The above characteristics allow to curry out the measurements with a high precision allowed for many laboratory researches.

Results and discussion

Calibration of Device using Antenna Setup

The previous analysis of EM radiation in the 4G range showed that due to the lack of an internal antenna, such an analysis can not be carried out without external antenna equipment; this conclusion is confirmed by the results shown in Fig. 3. The level of electromagnetic radiation in dB/m is shown here in the entire range of operation of the spectrum analyzer.

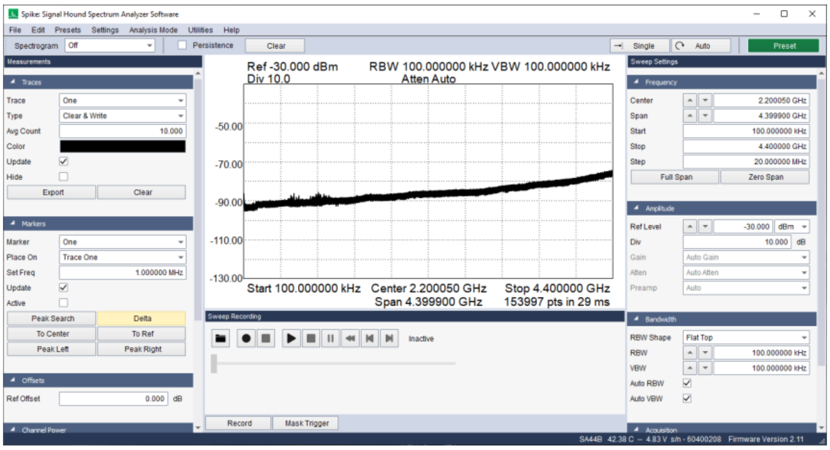

Fig. 3. The total level of radiation (noises) is in the analyzing range - without a receiving antenna.

At such measurement, the analyzer provide with the noise only in the extracted range. The whole accessible span from 100 kHz up to 4.4 GHz was analyzed. The reference level of amplitude is equal to -30 dBm, and RBW is assumed to 100.0 kHz, and VBV is also equal to 100.0 kHz. The level of extracted signal is less than -90 dBm at lower frequencies, and it groves slowly up to level of -85 dBm in the vicinity of maximal frequency 4.4 GHz. The spectral data are measured in the 153997 points with the step in time equal to 29 ms. The presence of any signal does not observed. Such level of noise allows to extract the signal with the low strength that makes possible to use the transmitting-receiving antenna with low gain in our setup.

In order to check the presence of EM radiation, the receiving array, consisting of four microstrip antennas was used. The antenna is connected with the spectrum analyzer USB-SA44B by standard 50 Ohm connecting cable. In Fig. 4, one can observe a series of the peaks of EM signal in the range of 4G stations. The first peak in the spectrum corresponds to the frequency 1.7 GHz of the PC processor is used in the measurement setup. The next four peaks correspond to the signals of the 4G stations received. The third sharp peak of the above corresponds to the signal of 4G station supplementing the connection with the institute Internet network. Unfortunately, the analyzer can not identify the Internet providers that does not give the information about belonging of the extracted signal to one or another operator. But the presence of separate peaks provides data about the number of active operators around the laboratory.

This can be provided by the special software sharing online. This information can be useful at the choosing the Internet operator, because strength of the signal is connected directly with the quality of the Internet communication.

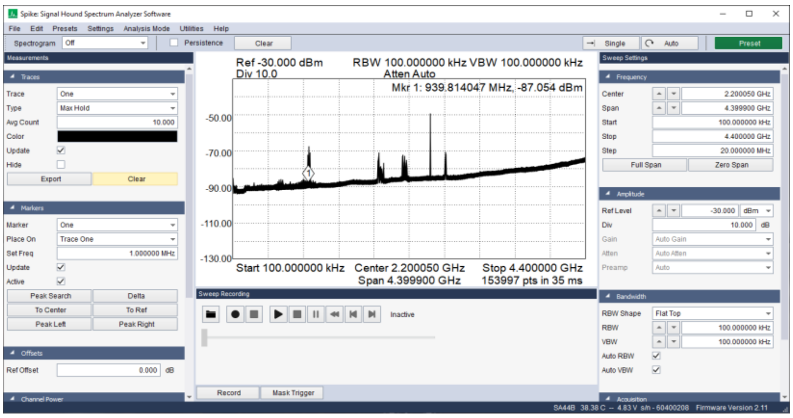

Fig. 4. The peaks of radiation in the range of 4G providers in the analyzing range – application of receiving antenna array.

The Analysis of the SA6 Signal Generator

The designed setup was used for checking the possibility to receive signals of the SA6 signal generator. The experiments were carried out at the frequencies 0.9 GHz, 1.8 GHz, and 2.4 GHz, at which the receiving-transmitting antenna, shown in Fig. 1, can operate. The spectrum of radiation is checked in the neighboring of 0.9 GHz in the frequency range equal to 50 MHz. The results presented in Fig. 5 demonstrate the existence of main peak corresponding to the work frequency of generator. The other two peaks with smaller values appear at the end of checked range. The extracted peak is clearly observed within the operating range. The above demonstrates a high selectivity of USB-SA44B at this central frequency.

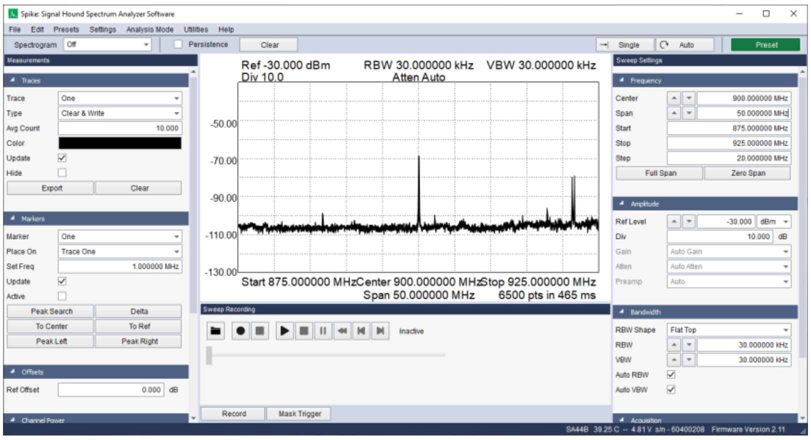

Fig. 5. The spectral radiation characteristic of generator SA6 at the generator frequency 0.9 GHz.

The measurements on the frequency 1.8 GHz demonstrate the analogous spectrum of radiation. There exists the clearly visible peak corresponding to work frequency of generator and other peaks corresponding to signals of G4 operators in the range from 1.8 GHz up to 2.2 GHz.

The different spectrum of radiation is observed at the frequency 2.45 GHz. For such central frequency at span 200 MHz, only one peak of radiation was detected and no visible radiation at the other frequencies. The results of measurements at this central frequency are shown in Fig. 6.

The extracted data in the specified span have simultaneous character, therefore in order to extract them at the fixed frequencies, the spectrum analyser allows to fix some frequencies, and the additional information about the sthength of the EM field appears in the screen.

The conducted experiments allow us to discover the separate signals for the frequencies up to 4.5 GHz. But, there no possibility to extract the real strength of signals because of low gain of the antennas used. In order to check that the strength of the received signal can be extracted with the higher characteristic values, the generator of the GPS signal at the working frequency 466 MHz was tested. The results of measurement are shown in Fig.7.

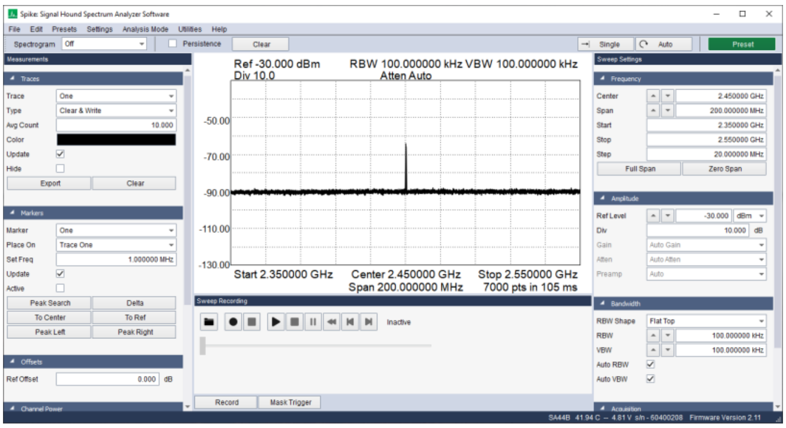

Fig. 6. The spectral radiation characteristic of generator SA6 at the generator frequency 2.45 GHz.

The extracted data demonstrate high strength of radiation equal to -26 dBm. The specific characteristic of radiation in the vicinity of central frequency is absence of the other sources of radiation because the checked range is lower of the 4G frequencies, and other sources of radiation are absent.

The Perspective System for Measurement of Human Exposure to EM Field from 4G Radiation

The proposed setup and the conducted measurements open perspective to develop the measurement system for human exposure to EM field radiation in the presence of 4G operations. The development of such system depends on the environment where the measurement is carried out, the 4G frequencies range, and the required parameters of exposure [25] – [27]. The scheme of the measurement setup is shown in Fig. 8.

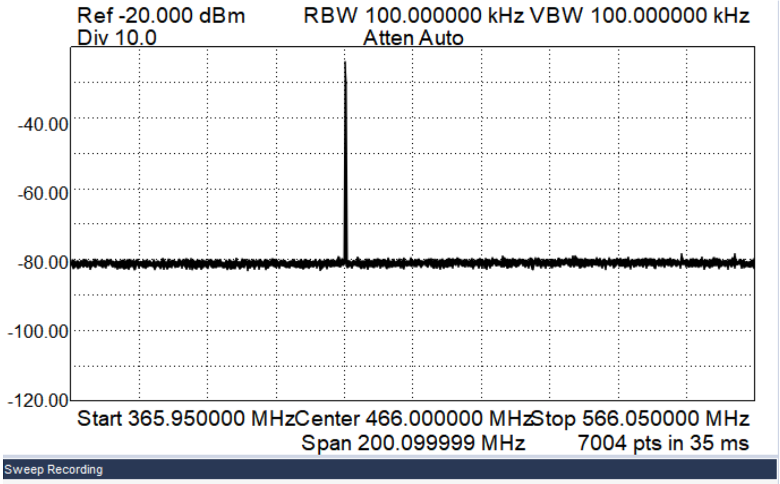

Fig. 7. The spectral radiation characteristic of the GPS signal generator at the generator frequency 466 MHz.

In the laboratory environment, the most researchers are mainly radiated by the EM field from their own mobile phones (or the near-field effects), therefore the EM field levels receiving by them are of huge interest to provide the EM compatibility. In this connection, the different factors (exclude the SAR parameters), namely the device's external radiated power, a working cycle of the signals, as well as the crest factor (CF) must be to taking into account at the various operational cycles. It is important to define the breaks in the time-amplitude variations of the released signals by the devices, which are connected to the 4G and characterized by the LTE (Long Term Evolution), as well as 5G in terms of the NR (New Radio) work networks, which are close to the human body. In order to explain such exposure, some new metrics using the external physical parameters, the characteristic of Instantaneous Power Density (IPD) was introduced [28].

One more definitive issue, which concerns to requirements of the exposure safety, is the determination of allowed limits from the transmitting antennas of RBS (Radio Base Station) (being into service). The above is usually estimated by both the measurements and calculations or simulations in the areas filled by the humans. Such determination of the allowed limits can be done by the variety of methods (see, for example, [26]).

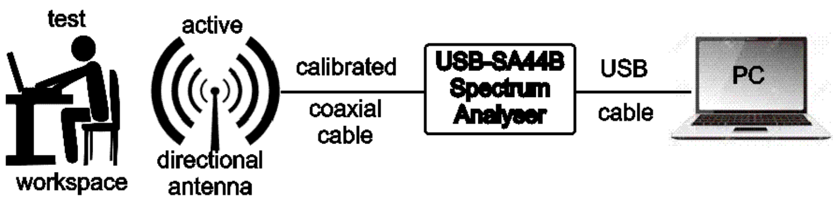

Fig. 8. The measurement setup for the fixation of human exposure to EM field.

The measurements are planning in the frequency range from 460 MHz up to 2.45 GHz to define all the sources, which may be appear in the measurement scenario. The extracted signals will be GSM traffic provider at 466 MHz, KyivStar operator signals at 1800 MHz and 2450 MHz. To evaluate investigated signal power characteristic, the value

$$R_{\max,\min} = 10\log(\frac{\max(P_{PBCH})}{\min(P_{PBCH})}), \quad (16)$$

is used for exposure of the EM field radiation [26]. The value P_{PBCH} is the power received by the collecting the Physical Broadcast Channel (PBCH) investigated channel. The sense of proposed characteristic is to determine the difference (in the dB) between the maximal and minimal values, which are experienced during some period acquisition. The lowest $R_{\max,\min}$, the better the signal stability and, correspondingly, the closer theoretical evaluation of the PBCH signal stability. Ideally, $R_{\max,\min}$ is characterized by the value of 0 dB.

Conclusions

The analytical formulas for calculation of the SAR absorbing by the human body are derived in the framework of the equivalent cylindrical monopole antenna model. The simple analytical formula for the SAR is derived that allows to simplify the procedure of comparing with the experimental data. The experimental setup to extract the spectral frequency radiation and getting the SAR values in the range of 4G operators is elaborated. It consists of the spectrum analyzer USB-SA44B supplemented by the respective software, notebook for analysis of signals, transmitting-receiving antenna array, and transmitting antenna, and signal generator SA6 is used for the measurements. The setup was calibrated using the signal generator, and it demonstrates the possibility to extract the spectral characteristics of radiation in the range from GPS to 4G operator frequencies. The perspective of approach is determination of the resonance frequencies supplemented the maximal values of SAR and verification the obtained values using the developed experimental setup.

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ОЦІНКА ОПРОМІНЕННЯ ЕМ ПОЛЯ В ДІАПАЗОНІ ЧАСТОТ 4G В ЛАБОРАТОРНИХ УМОВАХ

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Анотація. Метою роботи є оцінка випромінювання електромагнітного (ЕМ) поля на організм людини в діапазоні роботи 4G. Аналітичний підхід полягає в застосуванні концепції еквівалентної циліндричної монопольної антени, яка представляє заземлену людину. Виведено аналітичні формули, що дозволяють визначити напругу ЕМ поля. Експериментальна установка, що складається з аналізатора спектру USB-SA44B з відповідним програмним забезпеченням, ноутбука для аналізу сигналів, приймально-передавальної антенної решітки з чотирьох мікросмужкових антен, передавальної антени, що працює на частотах 0,9 ГГц, 1,8 ГГц і 2,45 ГГц. , а для вимірювань використовується генератор сигналів SA6. Розроблена установка демонструє можливість вилучення спектральних характеристик випромінювання в діапазоні роботи 4G, які в подальшому будуть використані для порівняння з даними моделювання. Помічено, що фіксована сила випромінювання залежить від джерел випромінювання. Перспективою розробки є оцінка SAR в лабораторних умовах.

Ключові слова: 4G випромінювання, приймально-передавальна антена, спектроаналізатор, зовнішнє калібрування, електромагнітне випромінювання, SAR

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