Date of publicationSEP-30, 2024, date of current version APR-24, 2024.
www.computingonline.net / computing@computingonline.net

Print ISSN 1727-6209
Online ISSN 2312-5381
DOI 10.47839/ijc.23.3.XXXX

EM Radiation Thermal Effects Simulation Study on a Realistic Female Model at Some Frequencies

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ABSTRACT The purpose of research is to develop a computer simulation based mobile phone safety testing scheme that is well suited for testing any mobile phone antenna at different communication frequencies and various realistic scenarios. It has been shown how feasible the study of realistic models is, what difficulties may occur, what effects, moments appear in the modeling process.

The aim of the study is also to show the need for changes in the standard of mobile phone safety testing and to investigate the possibilities of implementing these changes. It is preferable for manufacturers to perform testing using human realistic models through numerical calculations and conduct safety compliance testing under realistic conditions to produce more realistic picture. Computer modeling gives the possibility to consider various realistic models, realistic scenarios and different tissue dielectric properties according to the frequency.

It was investigated how mobile phone antenna radiation parameters (S11 reflection coefficient) change according to the various positions of the hand and fingers at standard communication 2100 MHz and 3700 MHz frequencies; were estimated Specific Absorption Rate (SAR) values in the human head and their dependence on S11 parameters were studied. Based on the obtained results, it has been shown that the preferred S11 behavior should be one of the indicators in the phone safety standards. For this, manufacturers should carry out mobile phone antenna matching/S11 parameter testing with free space.

KEYWORDS Electromagnetic field (EMF); SAR; S11; Inhomogeneous human model; FDTD method.

I. INTRODUCTION

SOON after the discovery of the electromagnetic (EM) fields, human began to use these fields widely in everyday life. In recent years, we have seen a rapid increase in the number of communication devices. It is especially clear that thelife is inconvenient and unimaginable without wireless communication devices, but it is also necessary to take into account the negative consequences that any technical progress can cause. Naturally, we are interested in how it influences and how it will be reflected on the human health.

The natural sources of EM radiation are the sun, stars, and others. The human body is adapted to the natural environment. The EM fields emitted by the human made electric devices, cause "pollution" of this natural background. Large areas are exposed to radio-frequency radiation generated by radars, communications and broadcasting services. However, the EM fields of industrial medicine [1]-[3] and consumer devices [4] cover only small areas. The problem of EM pollution of the environment has recently become extremely relevant, and, naturally, there has been interest associated with possible adverse effects on human health and in general on living organisms. It is worth noting the fact that, despite the many studies, there is still no categorical evidence that EM pollution is harmful to humans. Especially when the source of radiation is in the immediate vicinity of a person. The article [5] discusses the sources of EM radiation, their frequency range in which they appeared and its intensity. Based on international regulations and recommendations, safety measures have been developed and proposed that should be followed by everyone in case of high EM pollution. Some principles for preventing harmful effects are presented, as well as the safety limits for exposure to EM fields adopted by the ICNIRP, the Council of the European Union, the WHO [6]-[7].

The [9] study aimed to investigate whether exposure to Wi-Fi combined with UV (ultraviolet) radiation affects the inflammatory process in skin tissues. As a result, no protective effects from the undesirable negative effects of Wi-Fi radiation were found. At high frequencies of RF-EMF, mainly the layers of the skin absorb the energy of the radiated field. With the introduction of 5G and 6G technologies, the study of possible effects on the skin will become increasingly important.

Mobile phones are Radio frequency (RF) communication technologies. RF radiation is Non-ionizing radiation. Gamma, UV (ultraviolet) and X-radiation are ionizing radiation, have enough energy to penetrate deeply the tissues of living organisms and damage cells, change the DNA-structure [10]. Mobile phones do not have high power, but in the process of communication, the source of the EM field (phone antenna) is in close proximity to the head and the local impact on the body may exceed the established safety limit. In this regard, it is important to study the resulting effects of the EM field on a human and the EM background generated by various types of cellphone antennas [10].

The impact of the EM field on living organisms is manifested in the form of biological (non-thermal) and thermal effects. Non-thermal effects refer to some changes that occur at the cellular level, while the thermal effect refers to the heating of tissues and an increase in temperature. In most cases, biological and thermal effects influence each other and can occur simultaneously. However, this requires separate studies. [10].

Specific Absorption Rate (SAR), its measure is Watt per kilogram [W/kg] is a parameter that shows how much of the emitted RF field energy is absorbed per unit mass of a living body per unit time. SAR assessment is the most appropriate method for evaluating the RF performance of mobile phones and shows how well they meet FCC safety requirements. Safety requirements and recommendations are mainly based on WHO, IEEE, ICNIRP standards [7], [8], [10].

There are the following limitations in the existing recommendations: basic restrictions that must always be met; and limitations relating to the application of the primary limitations terms, which may be violated in certain cases. The main limitations are expressed by quantities that are not measurable and characterize the body, such as SAR. It should be noted that in the process of establishing safety standards, the environment in which a human is located during communication is not taken into account: room, car, hand effects, etc.

In [11], [12] the influence of the user's hand on the radiation pattern and on the impedance matching of a PIFA type antenna at the frequencies of GSM 900 and GSM 1800 systems was studied. The hand phantom was made from material based on agar and fabricated phantom numerical models were created using 3D scanning. Studies have shown that the hand, especially for the GSM 1800 band, significantly influences the quality of the radiation. The SAR at 1795 MHz was higher, but all the obtained values are corresponded very well to the maximum limits. In study [13] investigated influence of the hand on the antenna performance and absorption of the EM energy. Research was conducted mainly using the FDTD method. A model of a female head was considered with a hand holding a mobile phone at the cheek and in a tilt position. It has been shown, that the values of the SAR are reduced. The total absorption power increases rapidly with the influence of the hands. The influence of the hand significantly deteriorates the connection quality of the communication device.

Based on [14] research results, it can be assumed that the interaction of a biological object with a RF field depends on the location of the radiation source, frequency, orientation of the object to the source, the magnitude of the radio frequency field, waveform and the ability of the biological object to absorb and accumulate absorbed RF field energy. Correlation of the wavelength of the incident field with the geometrical dimensions of the biological system is also extremely significant.

The shape of the area with high absorption and magnitude of the RF field is determined by how well the phone's antennas together with the human's hand and head is matched with free space (S11 reflection coefficient). The value of the reflection coefficient-S11 depends on the relative position of the user's head, hands and fingers. This essential detail is not taken into consideration by companies when manufacturing mobile phones and testing their safety [15].

A study of the mobile phone EM field thermal effect on the inhomogeneous models of a child and a woman [13]-[15] by considering various configurations of holding the phone with fingers at frequencies of 900, 1900 and 3700 [MHz] showed that the hand influences the antenna matching conditions to the free space. As a result, the temperature rise and SAR values in the considered human head model are increased. The reason for these phenomena is the appearance of a standing wave and a high magnitude of the reactive field in the immediate vicinity of the antenna. In the presence of a hand, peak SAR and temperature rise values were significantly reduced for both child and adult head models. The main absorption of radiation energy occurs in the user's hand.

In [16] experimentally studied the change in the PIFA antenna S11 reflection coefficients at 900 MHz and 1800 MHz frequencies, caused by the interaction of the user's hand in different positions of holding the mobile phone (away from the head). Grip strength and hand size have been found to affect antenna performance, in some cases greatly.

A publication [14] shows the magnitudes of the SAR in the adult head tissues (at 1.575, 1.8, 2.4 [GHz]) are higher for a dipole antenna than for the case of the square-patch antenna. Therefore, it is important to define the correlation between the S11 parameters and SAR for various types of mobile phone antennas. Other studies [16]-[17] have examined the impact of handgrip on the performance of 5G devices and antennas. During the research process, it is difficult to fully take into account all the details but it will be possible to estimate the importance of them.

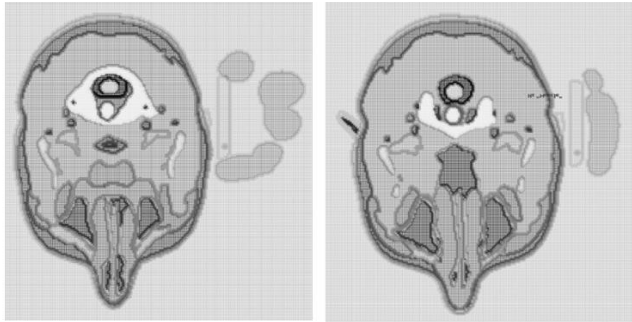
Presented work considers a study of the EMF thermal effects on a human in various cases, which is important to substantiate and generalize the conclusions. Our goal was to study how different head to phone intervals (1, 10, 20 [mm]), hand-head mutual configurations affect a well-matched dipole antenna at the 2100 MHz and 3700 MHz frequencies. Various parameters effects on the S11 reflection coefficient values were studied. For all possible scenarios, the distributions of SAR and EM fields were investigated. An analysis of their magnitudes in relation to the efficiency of a dipole antenna has been implemented. Significant novelty in the presented study is to determine the correlation between S11 and SAR for all realistic cases of an EM exposure, considering that the emitted power instantly increases when the matching of the antenna (matching conditions) is deteriorated.

II.RESEARCH METHOD AND MATERIALS

It is known that conducting real experiments on humans is prohibited, so the problem can only be investigated using computer simulations. The only way to assess the thermal impact of EM fields on a person is to create a mathematical algorithm and an appropriate computer model for numerical experiments. It is also impossible to place an EM sensor in the human body. For such experiments, it is extremely important to develop and expand the possibilities of EM processes modeling. Computer simulations allow for the consideration various realistic models, realistic scenarios and various frequency dependent dielectric properties of tissues.

FDTD – the method of finite differences in the time domain is used to solve problems of diffraction on biological bodies of complex inhomogeneous shape. FDTD is the most suitable mathematical method for the computational analysis of inhomogeneous objects of complex shape, such as the human body. Therefore, FDTD method was used to conduct a study of realistic inhomogeneous human models. A big disadvantage of the FDTD method is that we cannot estimate the calculation error by assessing the “fulfilment” of electrodynamic conditions at the boundaries of body inhomogeneity. To apply the FDTD method, it is necessary to discretize the study area. The electrodynamic process occurring in each grid cell of discrete areas is considered simultaneously at each moment of time. It should be noted that in order to improve the accuracy of solving the problem, it is necessary to reduce the discretization size or, in other words, increase the number of discretization cells. Using the FDTD method in diffraction problems and taking into account the capabilities of a computer, we are limited in the geometric dimensions of the study area. All this requires a very powerful computing resource or, accordingly, a rather large calculation time.

(a) (b)



(c) (d)

Figure 1. Studied configurations of the human hand-head models (a), (b). Corresponding discrete models in horizontal section (c), (d) [14].

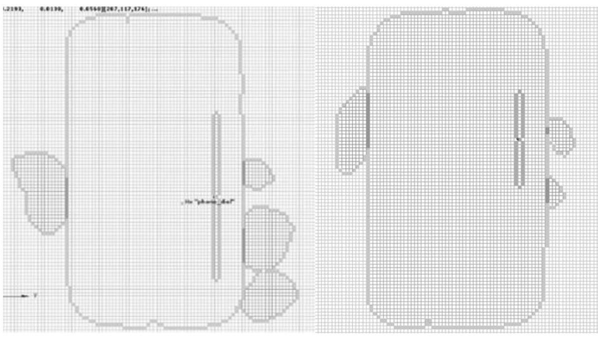
Numerical experiments were performed using the FDTD software package (FDTDLab) developed in Laboratory of Applied Electrodynamics and Radio Engineering (LAE) based on the FDTD method [14], [15]. For each performed numerical simulations, the size of each discrete grid cell of the study area is one millimeter. A 3D heterogeneous adult discrete model from “virtual population” (Ella-female model) was also used. The files of the considered models have the *“.cells”* extension and can be opened by the FDTDLab software package. Using the support program MyFDTD it is possible to create desired new scenarios, move a specific part of the human body model, such as the head, define a new shape of the antenna, etc.

To fix the position of the phone near the head and the hand model with different finger configurations were processed using the 3D MAX graphics program. The model of the human head in the considered case contains 47 types of different tissues.The dielectric properties for each fabric are taken from the IT'IS Foundation database. The arm model is homogeneous and was filled with muscle material only. To simulate the exposure on human, a sinusoidal form of mobile phone dipole antenna radiation was used for 2100 MHz and 3700 MHz frequencies [14], [15].

The paper presents the numerical experiments results with the following configurations of gripping a mobile phone with a hand: Hand 1 – when the hand freely holds the phone with fingers during communication. The palm of the hand moves away from the phone. Hand 2 – during communication, the phone is firmly held by the fingers, the palm touches the phone body. Various distances between the head and the hand models with the phone were also studied (1, 10 and 20 millimeters). The selected configurations of the studied models are shown in Fig. 1a, 1b. A discrete model of a human head – a hand with phone model in a horizontal section are presented in Fig. 1c, 1d.

III. THE RESEARCH FINDINGS AND DISCUSSION

It is known that the EM field of a phone antenna in the information emission mode (as well as in the reception mode) is divided mainly into two regions: the near field together with the Fresnel zone, where a traveling wave is formed, and the far field is already a traveling wave [13]. The size of the near field depends entirely on the design of the antenna, the geometry of nearby objects (in our case, the hand with which the user holds the phone, the head and even his body) and the wavelength of the emitter. In the far zone, the fields E and H are in phase and have the form of a traveling wave, and their ratio is equal to the open space impedance. At the same time, in the near field of the antenna, with poor antenna matching due to the hand, strong and high-amplitude standing waves arise in the form of a reactive field. As a result, the energy absorption of the EM field in the user's body will increase and the SAR value will become higher. In this zone, the E/H ratio changes significantly and depends on the conditions for matching the antenna with free space. With the best matching of the antenna parameters, a low value of the reactive electric field strength is achieved and a traveling wave is created in the near zone. Since the size of the hand and head and their location can be compared to the wavelengths of the mobile phone range, their location (position) determines the condition of the traveling wave. Reflected waves are generated by any change in the propagation path of the EM field; their phase shift affects the matching of the antenna with free space. Because of good matching, we will have just such a traveling wave that flows along the surface of the object with the minimum power supply voltage that is necessary for a reliable connection to the base station. In the near field of the antenna, there is a mostly reactive field, which means that the E and H fields are out of phase, in contrast to the traveling wave, where these fields are in phase.

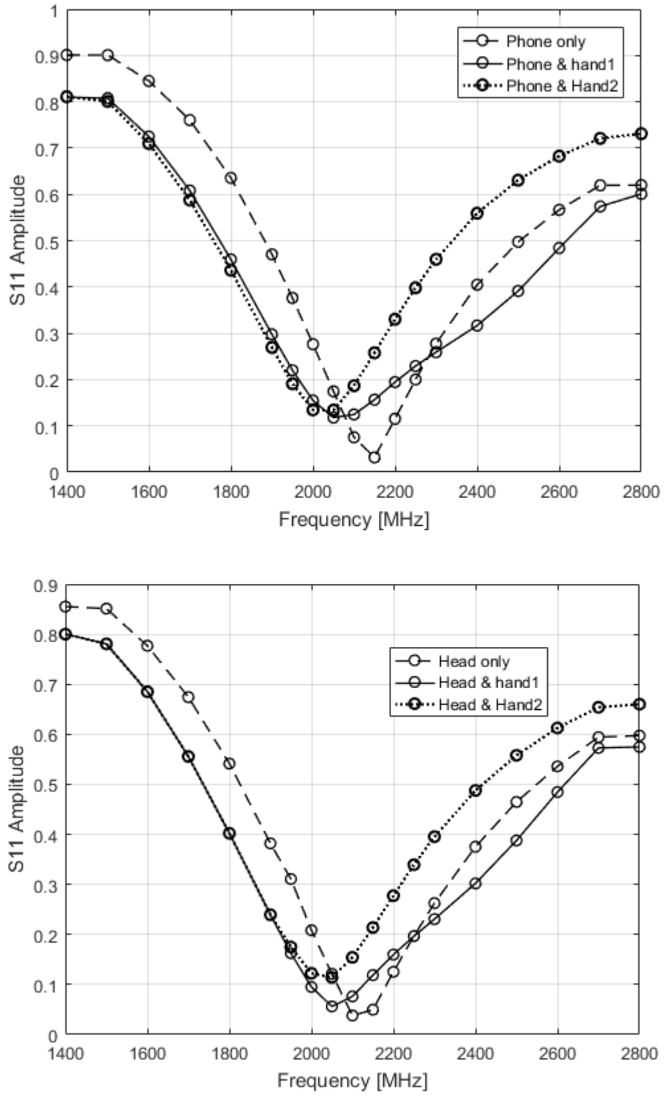


(a) (b)

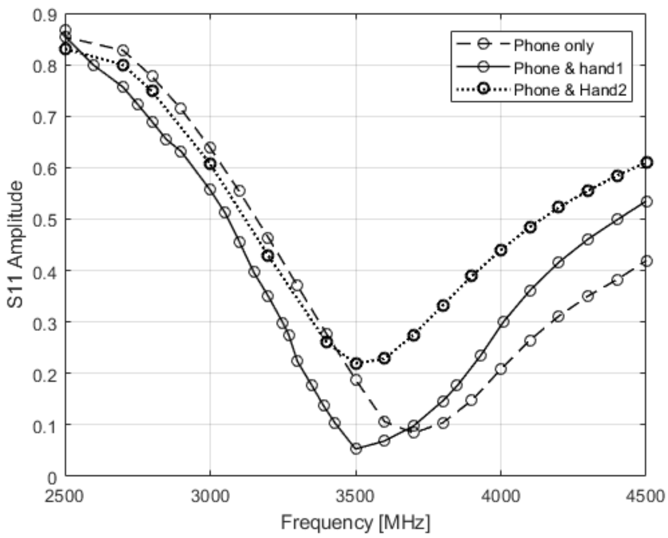
Figure 2. Mobile phone discrete models with dipole antenna at: (a) 2100 MHz, (b) 3700 MHz frequencies

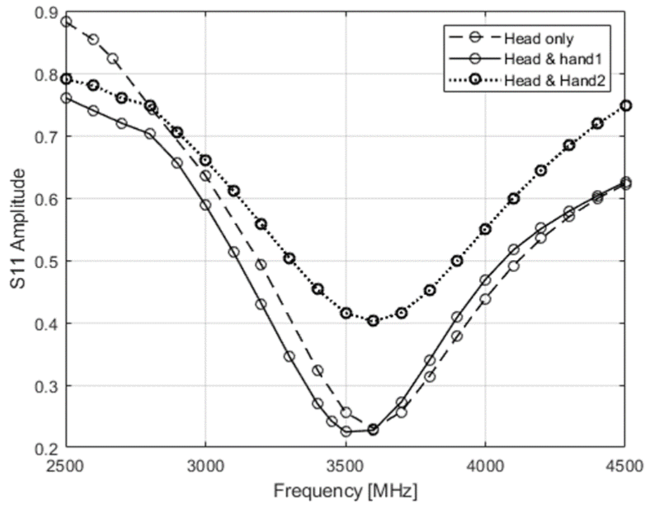
The purpose of this research was also to study the above effects in order to form some recommendations for mobile phone users to minimize exposure to EM field. In particular, how best to hold the phone by hand when using it.

For numerical experiments, a dipole antenna was chosen as a mobile phone antenna. For frequencies of 2100 MHz and 3700 MHz, the dipole length was selected so that the S11 reflection coefficient values would be as small as possible. In this case, the antenna is resonant and is in good matched with free space. We studied the frequency characteristics for the dipole antennas of the considered length. Computer modeling was performed for all selected hand configurations without considering the influence of the head and when the effect of the head is taken into account. L1- length of the dipole antenna for 2100 MHz frequency is 48 mm and the lowest S11 equal to 0.08. For 3700 MHz, L2 equal to 26 mm and the minimal magnitude of the parameter S11 equal to 0.0842 (Fig. 2).



(a)

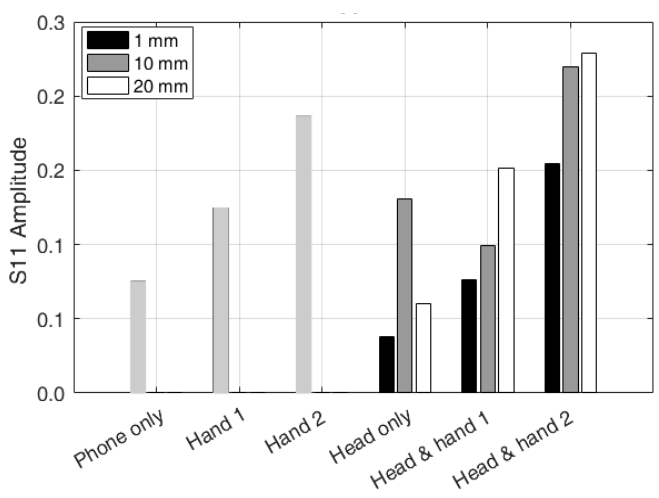




(b)

Figure 3. Dipole antenna frequency characteristic: (a) for L1 at 2100 MHz and (b) for L2 at 3700 MHz frequencies.

As shown by the results of computational experiments (Fig. 3), dielectric objects in the form of a head and a hand, located in the immediate vicinity of the antenna, have a significant effect. In particular, it increases the value of the reflection coefficient S11 both for frequency of 2100 MHz and for frequency of 3700 MHz and shifts the frequency response of the antenna. In practice, these effects affect the conditions for "matching" the phone antenna with free space. As a result of the connection deterioration between the phone and the base station, an increase in the radiation power is triggered in modern phones and, as a result an increase in exposure is expected (SAR).



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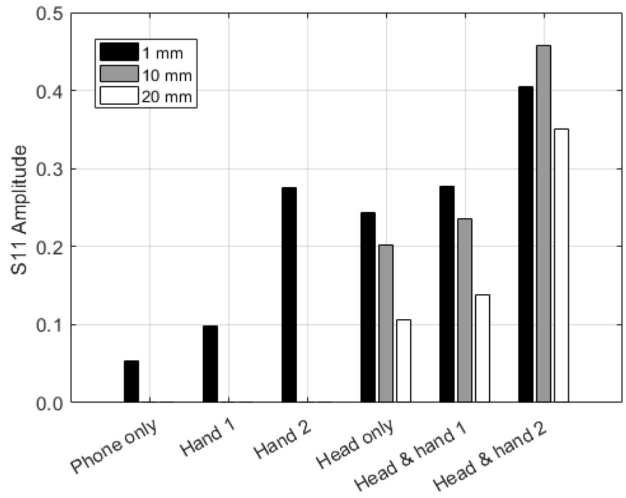


(b)

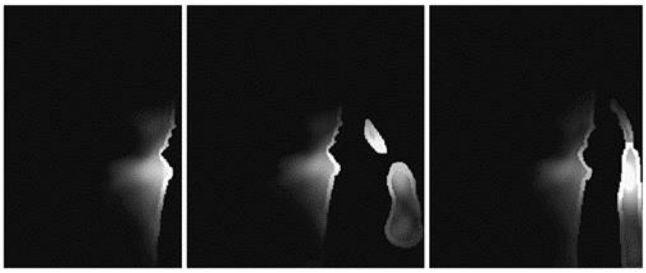
Figure 4. "Head- hand-antenna" system S11 reflection coefficient values at (a) 2100 MHz and (b) 3700 MHz frequencies.

Fig. 4 shows the results of calculations at fixed frequencies, from which it is clearly seen how S11 reflection coefficient changes due to the effect of the head and hand on the radiation characteristics of the antenna and, accordingly, how the conditions for matching the antenna with radiation change. It can be seen that if the palm (Hand 2) covers the mobile phone antenna, the matching condition worsen (without taking into account the influence of the head or with the head) than when the mobile phone is held with spread fingers (Hand 1). Obviously, the latter form of holding the phone with fingers is preferable.

As mentioned, SAR determines the absorption of EM power by tissue mass [10]. Depending on how the SAR is calculated, it can be point SAR or averaged over a certain mass. The need for SAR averaging is due to the fact that the SAR measured in a real experiment does not match the point SAR obtained by numerical methods. It was found that the averaged SAR matches the actual experimental values much better. That is why the safety standards mention exactly the averaged SAR. The available tools and the millimeter discretization of anatomical models are the basis for the question of the choice of mass averaging. According to the modern IEEE safety standards, the maximum value of SAR in the fabric should not exceed the specified value. Similarly, whole-body and space-averaged SAR values are constrained. Generally, averaging in space is done according to mass, for example in the presented study in a cube with mass 10g (10g SAR) [10].

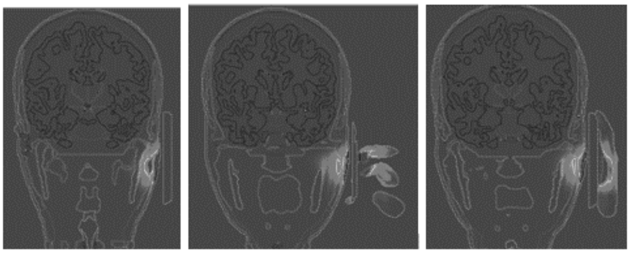
In the mobile frequency band, the magnitude of the EM field strength determines the SAR value for a given phone. With a better matching of the antenna parameters, a low intensity of the reactive EM field is achieved. It is important to study and understand the nature of the process of EM exposure of a mobile phone antenna to a person. For this antenna matching analysis, the distribution of SAR in human hand and head models were studied. The results obtained showed that the model geometry strongly affects the EM field structure. It is clearly seen that tissues absorb part of the radiated energy. This phenomenon is partially reflected in the behavior of S11 reflection coefficient.

The distributions of point SAR in the head and hand models are shown in Fig. 5 and Fig. 6. Can see that the maximum SAR value is concentrated in the hand model. Since most of the EM field energy is absorbed by the hand and the peak SAR values in the tissues of the human head model are significantly reduced.



(a) (b) (c)

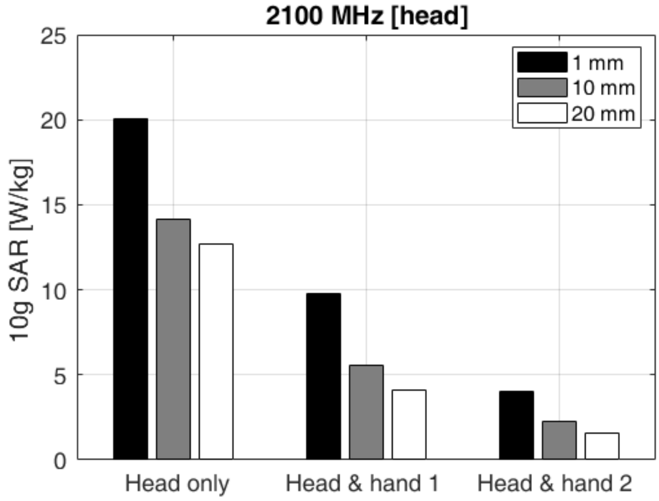
Figure 5. Distribution of SAR within the human hand-head models. Head: (a) – without a hand; (b) -with Hand 1 and (c) with Hand 2 at 2100 MHz frequency.



(a) (b) (c)

Figure 6. Distribution of SAR within the human hand-head models. Head: (a) – without a hand; (b) -with Hand 1 and (c) with Hand 2 at 3700 MHz frequency.

Fig.7 and Fig. 8 represents SAR values within the head-hand models for 2100 MHz and 3700 MHz frequencies respectively. It is clear that the dependence between 10g SAR values and the distance of the phone from the human head model is inversely proportional. As far phone from head is lower, the value of the 10g SAR becomes within the head model. Due to the hand effect, peak SAR values in head tissues are small. When the hand palm covers the phone antenna, the peak SAR values are smaller than the first hand position holding the phone – Hand 1. This can be justified as follows: only a small part of the EM field energy penetrates and is absorbed in human head tissues. The hand absorbs most of the EM field energy emitted by the antenna. As a result, the signal of the base station decreases, but in this case, since all modern phones have Automatic-Gain-Control, the radiated power of the antenna increases automatically.



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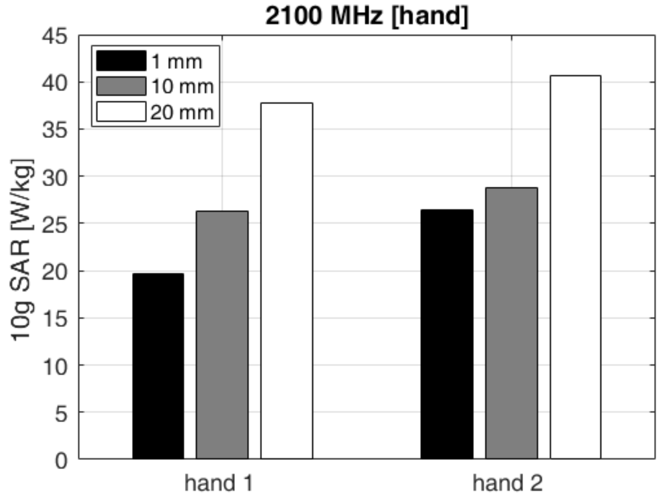
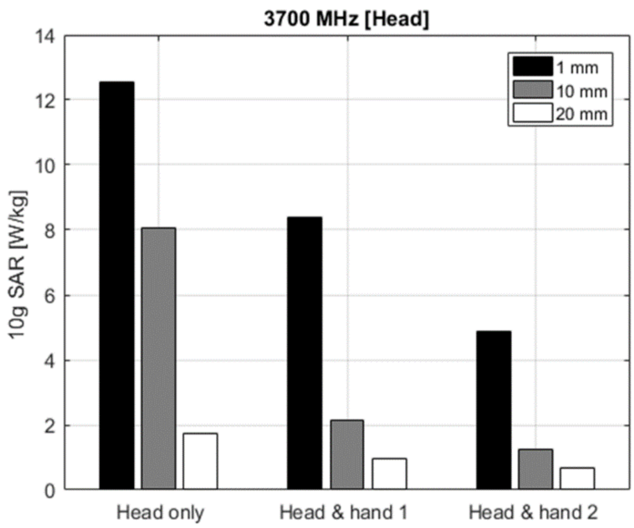


(b)

Figure 7. Values of the 10g SAR for different distances phone to head. (a) Within the head and (b) within the hand models at 2100 MHz frequency.



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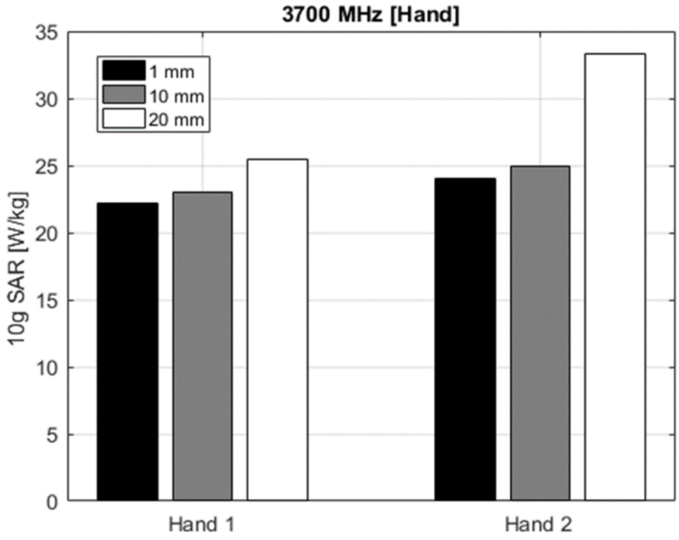
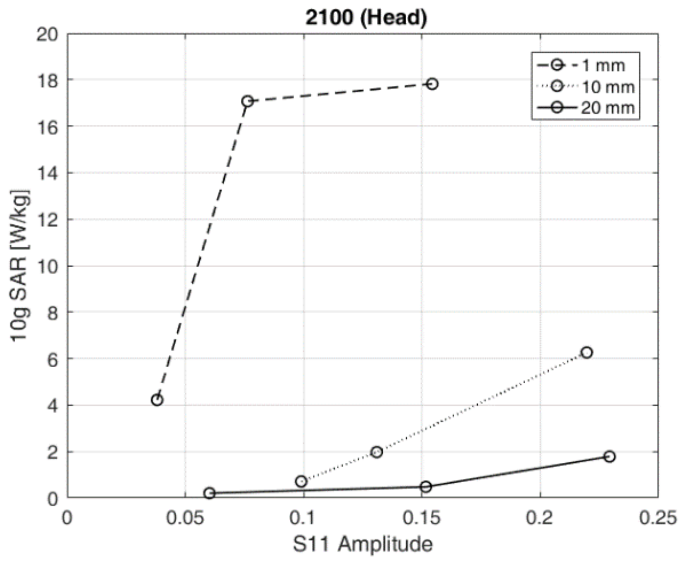


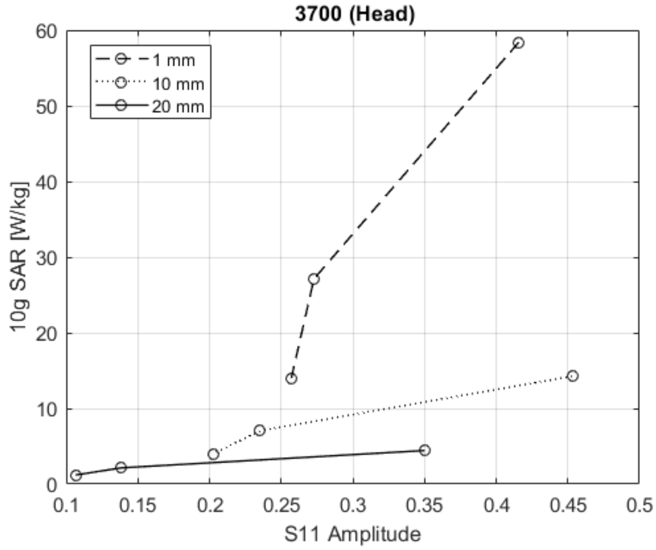
(b)

Figure 8. Values of the 10g SAR for different distances phone to head. (a) Within the head and (b) within the hand models at 3700 MHz frequency.

Dependence of peak values of 10g SAR on S11 reflection coefficient values is demonstrated in Fig. 9 for both considered frequencies. SAR values normalization were carried out on EM field values of the phone antenna in far-zone. On each graph the first point matches to the SAR value for head only; second point for "head-Hand 1" system; third point for "head-Hand 2" system. The head-hand mutual positions have a prominent influence on the values of the antenna S11 reflection coefficient i.e. conditions of the matching to the free space.



(a)



(b)

Figure 9. 10 g SAR (S11) dependences: (a) at 2100 MHz, and (b) at 3700 MHz frequencies with consideration AGC.

Peak 10 g SAR values are highly dependent on the S11 parameter and the distance between the phone and the head. When holding the mobile phone tightly (Hand 2) and covering antenna with hand, the matching of the antenna with free space is noticeably, worsen. (Fig. 9a, 9b). Its insufficient matching for radiation causes the appearance of a reactive field around the antenna. At this time, part of the energy delivered to the antenna is returned, which reduces the efficiency of the antenna. The lower the degree of matching of the antenna the higher the amplitude of the reactive field and the larger its area. Since the reactive field area is large compared to the size of the phone along with the hand, it covers the surrounding objects such as the head, hand, ear. As a result, in the case of a strong reactive field, the absorption by the head model is greater. Thus, poor antenna matching leads to increased peak SAR values in the human head-hand system. Well seen that the model parameters selection also significantly influences on the obtained results. A high reactive field can be harmful to the users and antenna device itself. Therefore, an important problem in antenna systems is their high degree of matching and, as a result, reducing the amplitude and size of the reactive field.

VI. CONCLUSIONS

Influence of the human hands (fingers) positions on the mobile phone antennas matching to the free space at 2100 MHz and 3700 MHz frequencies were deeply and thoroughly investigated. The possible thermal effects of RF EMF on human were studied. The possible negative effects associated with these impacts have cumulative nature and may appear in the future. Of particular note are the harmful effects on children. They are exposed to RF radiation from an early age. Their brain is the mainly target for EM radiation. The children nervous system, the skull and brain are still unformed, more permeable to the radiation than adults and undesirable consequences on children in future may be more severe [10]. Results of previous studies have showed that the head, and especially the hand, can further degrade radiation efficiency. Their geometry and the position of the holding mobile phone are important [16]-[19]. The potential health risks associated with EMF exposure are obvious because people live in environments where they are constantly exposed to EMF [20]-[25]. A review of studies indicates that there is a risk of some biological effects at the frequencies planned for 5G [26]-[27].

Based on our previous studies and the summary of the obtained results within presented research could be proposed that manufacturers should pay attention hand effects in the testing and production process of mobile phones and existing international safety standards need to be revised. Preferred S11 reflection coefficient behavior should be one of the indicators in the phone safety standards. For this reason, manufacturers should carry out mobile phone antenna S11 parameter testing in free space. It is preferable for manufacturers to perform testing using human realistic models through numerical calculations and conduct safety compliance testing under realistic holding conditions of the mobile phones by the users to produce a more realistic picture. For this purpose, an outline of the numerical testing procedure within the presented paper was developed. A computer simulation based mobile phone safety testing scheme was elaborated, so that it is well suited for testing any mobile phone antenna at different communication frequencies and various realistic scenarios. If the antenna of the mobile phone is well matched to the free space, it does not radiate in the direction of a user's head, completely re-radiates the delivered power and does not change the S11 parameter of the antenna even in the immediate vicinity of the head and hands. Then the antenna is ideal and the impact of the head and hands does not change the antenna matching conditions.

It will be desirable that the international organizations such as ICNIRP, The Bioelectromagnetics Society, European Bioelectromagnetics Association, IEEE, European Telecommunications Standards Institute, FCC, etc., as well as the companies who develop 5G systems, to be interested in the results of the present research. Obtained results may be of significant importance to these Institutions, which may have an important impact on the relevant industry and the wider community, as well.

ACKNOWLEDGEMENTS

Research at TU Ilmenau (Germany) is financially supported by joint Rustaveli-DAAD 2022 fellowship programme – Grant number 04/12, 05/25/2022; ID – 57646330.

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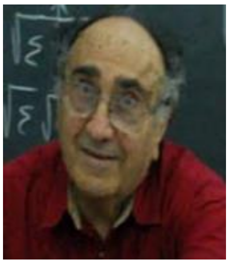

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