Progress In Electromagnetics Research, PIER 77, 225–242, 2007

INTERACTION OF DUAL BAND HELICAL AND PIFA HANDSET ANTENNAS WITH HUMAN HEAD AND HAND

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Abstract—Helical antenna and planar inverted-F antenna (PIFA) are two commonly used handset antennas. This paper presents a comprehensive study on the performance of a dual band PIFA and a dual band helical antenna designed for operating in GSM900 and DCS1800 frequency bands. Radiation patterns and VSWR of these antennas are computed in free space as well as in the presence of head and hand. The specific absorption rate (SAR) of the helical antenna is calculated and compared with that of the PIFA handset antenna. The peak average SAR in the head is compared with SAR limits in the safety standards and so the maximum radiation power of each antenna is determined. In addition, radiation efficiencies of these handset antennas are computed in the presence of head and hand. All numerical simulations are performed using the Ansoft HFSS software. Numerical simulations results are in good agreement with published measurement results.

1. INTRODUCTION

Interaction of handset antennas with human body is a great consideration in cellular communications. The user's body, especially head and hand, influence on the antenna voltage standing wave ratio (VSWR), gain and radiation patterns. Furthermore, thermal effect, when tissues exposed to unlimited electromagnetic energy, can be a serious health hazard. So standard organizations have set exposure limits in terms of the specific absorption rate (SAR) [1, 2].

Simplified phone antennas such as half-wavelength dipoles in free space or quarter-wavelength monopoles mounted on a metallic box have been frequently investigated in the literature. These antennas are no longer in widespread use for cellular phones and therefore it is not suitable to use them for studying the interaction of handset antennas and nearby tissues. However, when it is desired to focus on the human body modeling it is reasonable to use a simple monopole or dipole antenna [3, 4]. At the present time PIFA and helical antennas are two commonly used handset antennas. Today, the handset antennas are designed to be able to support two or more frequency bands of various cellular networks. It is required to perform a comprehensive study to determine which handset antenna has better performance and less health hazard. Also it is needed to determine which frequency band is better for operation.

In one of the first investigations in this area [5], a comparative study has been performed among a monopole antenna and some different types of single band PIFA antennas. Size of the investigated antennas and length of handset boxes used in [5] are considerably greater than those used today. SAR and temperature rise in a human head have been calculated for electromagnetic radiation from a monopole, single band helix, single band patch and side mounted single band PIFA antenna at 900 MHz and 1800 MHz [6]. Effect of the separation distance between the antenna and user head has been studied for a dual band PIFA handset antenna [7]. This study has shown that there is a proportional relation between SAR and antenna efficiency. In [8], SAR induced in a cubic head model by two single band helical antenna, one radiates at 900 MHz and the other radiates at 1800 MHz, has been calculated and the effect of mobile shell material has been studied. SAR and radiation efficiency has been measured for four types of PIFA designed for the PCS frequency band (1850 MHz–1990 MHz) and it has been shown that handsets with higher-efficiency antennas might not necessarily have higher total radiated power due to the SAR limit [9]. The head loss for twenty different mobile phones, with external and built-in antennas, has been measured [10]. The measured results have been compared, it has been shown that the handsets with built-in antennas are much less sensitive to how the phone is held than the handsets with external antennas. In [11], interaction of a single band helical antenna, mounted on a metallic box, with a human spherical head model has been investigated and reported. SAR level in head from a monopole, a helix and a patch antenna at 1.8 GHz has been computed and it has been shown that the patch antenna produces the lowest SAR in the head tissues [12]. For a helical antenna operating at 900 MHz, the SAR quantity, radiation patterns and radiation efficiency in the presence of human head and hand has been computed [13]. In another investigation, interaction of a dual band gap loop antenna with human head and hand has been investigated [14].

In this paper, performance of a dual band helix (as an external antenna) and a dual band PIFA (as a built-in antenna) is evaluated in the presence of head and hand model. In this study, all radiation characteristics including radiation patterns, radiation efficiency and VSWR are examined. In addition, the SAR quantity is computed for both the helical and PIFA antennas. Both of the investigated antennas are designed so that they cover the frequency bands of GSM900 (890 MHz–960 MHz) and DCS1800 (1710 MHz–1880 MHz). As pointed out before, all numerical simulations are performed using the Ansoft HFSS software.

2. POWER ABSORPTION AND SAR

Energy absorption in biological tissues is characterized by Specific Absorption Rate (SAR). SAR is defined as the time derivative of the incremental energy (dW) dissipated in an incremental mass (dm) contained in a volume element (dV) of a given density (ρ) [15, 16]:

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) \quad \text{(W/kg)} \tag{1}$$

The SAR quantity is related to the internal E-field by:

$$SAR = \frac{\sigma E^2}{\rho} \quad \text{(W/kg)} \tag{2}$$

where, ρ is the mass density in kg/m^3 and E is the root mean square (rms) of electric field strength in volts per meter. The concept of SAR is meaningful only in the frequency range between approximately 100 kHz and 6 GHz–10 GHz, i.e., where the penetration depth of the electromagnetic energy in the tissue is of the order of 1 cm or more [16].

The local SAR averaged over a specified 1 gram or 10 gram mass, is called 1-g or 10-g spatial average SAR. Comparison of averaging procedures for SAR distributions has been presented in [17].

If the metabolic heating rate, blood flowing cooling rate and the heat losses rate for a tissue have been neglected, the relation between

SAR, duration of exposure (dt) and change in temperature (dT) is [18]:

$$\frac{dT}{dt} = \frac{SAR}{c} \quad (^\circ\mathrm{C/s}) \tag{3}$$

where, c is specific heat capacity (J/kg °C). Thus, a SAR of 1 W/kg is associated with a heating rate less than 0.0003°C/s in muscle tissue ($c = 3.5$ kJ/kg °C), a very small heating rate since it would take more than 1 hour to increase the temperature 1 degree Celsius.

If we consider the effect of blood flow and metabolic heating rate, the temperature change due to the induced SAR can be obtained by solving the bio-heat equation [19].

3. HEAD AND HAND MODEL

Biological tissues are modeled by their permittivity and conductivity. The complex permittivity (ε) of a biological tissue is given by:

$$\varepsilon = \varepsilon_r \varepsilon_0 + j\frac{\sigma}{\omega} \tag{4}$$

where, σ (S/m) is the conductivity of tissue in siemens per meter and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. The relative dielectric constant (ε_r) and conductivity of various tissues over the frequency range of 10 kHz–10 GHz are available at [20, 21].

High-resolution models of the human head derived from magnetic resonance imaging (MRI) scans [22] can provide accurate results, however such a detailed model requires a lot of computational time in the numerical methods [23]. Compared with a real head, flat and cubic model of head may cause considerable changes in antenna loading [15]. Spherical models of appropriate diameter provide a reasonable accuracy for power absorption characterization. It should be noted that when a spherical structure is used for modeling the head, the tilt angle of the nearby handset can be neglected.

In this paper a simplified homogeneous spherical head model will be used. Diameter of this spherical model is 213 mm and properties of the head tissue-equivalent dielectric for both the GSM and DCS frequency bands are shown in Table 1. For computation of SAR the head tissue density is assumed to be 1000 kg/m^3 [15].

In the majority of studies, SAR induced by a handset is computed without a hand. Neglecting the effect of hand usually results in an overestimation of the SAR in the head [15]. This overestimation leads to have more safety factor when the head SAR computations compared with the standards. Moreover numerical and experimental studies have shown that SAR in the hand is low compared with the SAR

Table 1. Properties of the tissue-equivalent dielectric used for the spherical head model [15].

Frequency	Relative permittivity, ε_r	Conductivity, σ (S/m)
900MHz	41.5	0.97
1800MHz	40	1.4

in the head [15]. However, the effect of hand on the antenna radiation characteristics is significant and can not be neglected [5, 24].

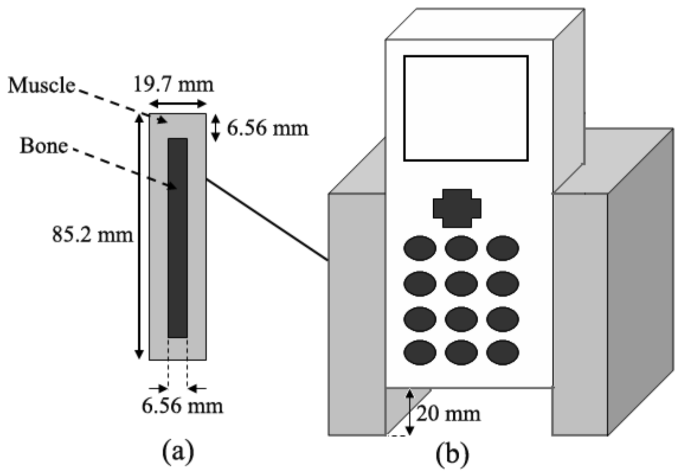


Figure 1. Simplified model of the human hand. (a) Cross section of the hand model [5]. (b) Position of a handset placed in a hand.

As illustrated in Fig. 1, in this paper we use a simplified model of hand [5] in which a layer of bone is surrounded by a layer of muscle. This model covers three sides of the handset. Dielectric properties of tissues used in hand model are shown in Table 2 [21].

In all numerical simulations, it is assumed that dielectric properties of tissues are constant over the entire GSM or DCS bandwidth.

The relative distance between the head and handset has a strong influence on SAR. Under normal use conditions of a handset, it touches the ear. To take into account the effect of ear thickness, we assume that the handset is held at a distance of 5 mm from the head. It should be noted that when the handset is held at 5 mm from the head, the

Table 2. Properties of tissues used for the human hand model [21].

Frequency	Muscle		Bone	
	ε_r	σ	ε_r	σ
900MHz	55.03	0. 943	12.454	0.1433
1800MHz	53.55	1. 34	11.78	0.275

effect of shoulders on the SAR induced in the head is negligible [15]. Fig. 2 demonstrates the simulation configuration that will be used for analysis of handset antenna performance in the presence of human head and hand.

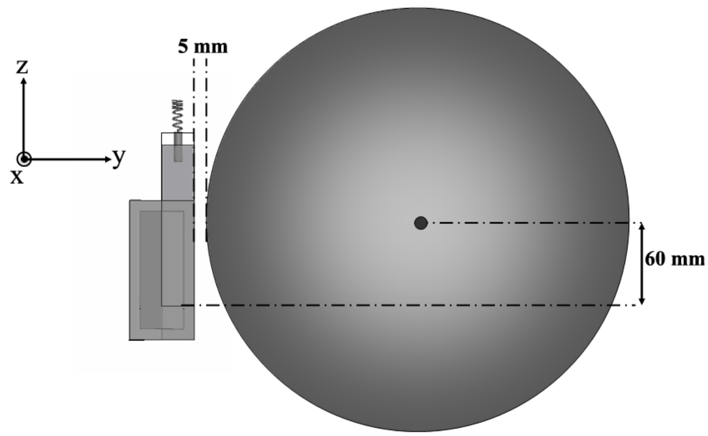


Figure 2. Position of handset, hand and head in numerical simulations.

4. VALIDATION OF NUMERICAL SIMULATIONS

To verify the validity of numerical simulations we first perform a validation test and compare its results with published measurement results. As shown in Fig. 3, in the measurement setup [25], a spherical-like head phantom is irradiated by a half-wave dipole antenna at 835 MHz. Length of dipole is 178 mm and it is placed at several distances from outer surface of the sphere. The phantom, shown in Fig. 3, is consisting of an outer glass shell and the head tissue-equivalent material. Inner diameter and thickness of the glass shell are 213 mm and 5 mm, respectively. Electrical properties of the glass

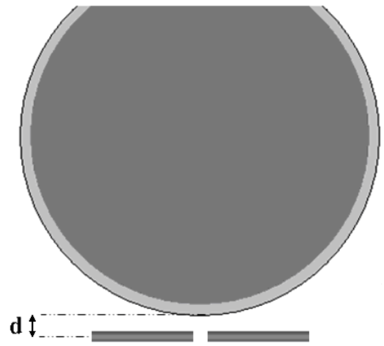


Figure 3. Exposure of a spherical head phantom by a half-wave dipole antenna at 835 MHz. Measurement results [25] are used for validation of numerical simulations.

Table 3. Properties of the spherical head phantom used for validation test [25].

Frequency	Glass shell		tissue-equivalent material	
	ε_r	σ	ε_r	σ
835MHz	4	0	41.1	1.06

Table 4. Comparison of measurement [25] and simulation results for peak 1g-SAR in head equivalent liquid (Fig. 3).

d (mm)	Peak 1g-SAR measured	Peak 1g-SAR simulated	Error percentage
5	6.78	7.27	7%
15	3.41	3.24	5%
25	1.85	1.65	10%

shell and the head tissue-equivalent material are shown in Table 3. The depth of the liquid material in the glass shell must be more than 15 cm to minimize the reflections from the upper surface [15]. Table 4 compares the measured [25] and simulated peak 1-g SAR for three different distances d between the radiating dipole and the phantom. The SAR quantity reported in Table 4 is normalized to the output power of 0.5 W. The output power is sum of the absorbed power in the human body and the radiated power to the far field. As shown in Table 4, numerical simulations results are in good agreement with the measurement results.

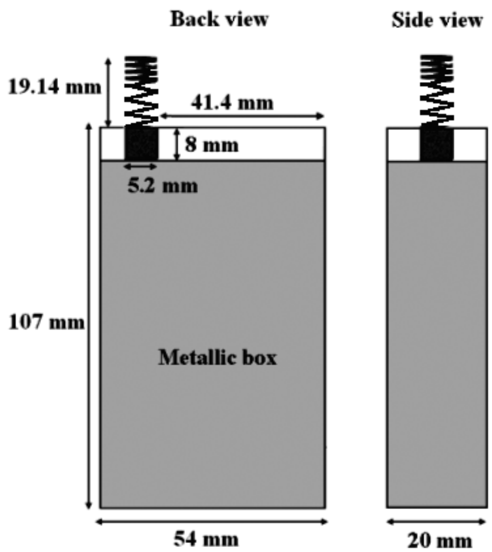


Figure 4. Dual band helical antenna placed above a handset.

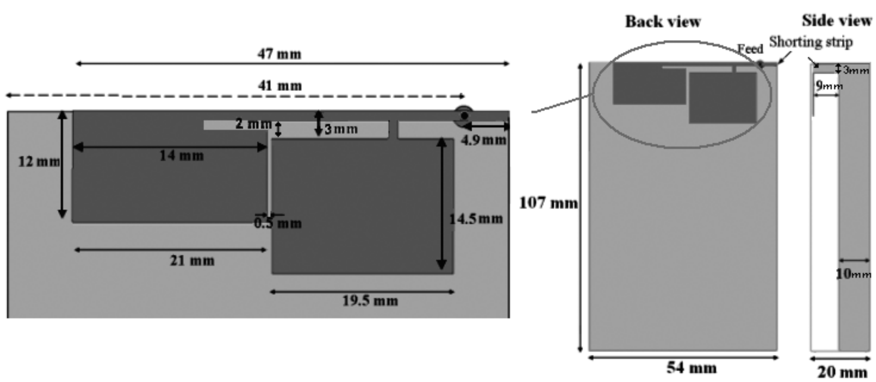


Figure 5. Dual band PIFA handset antenna.

5. DUAL BAND HELICAL AND PIFA HANDSET ANTENNAS

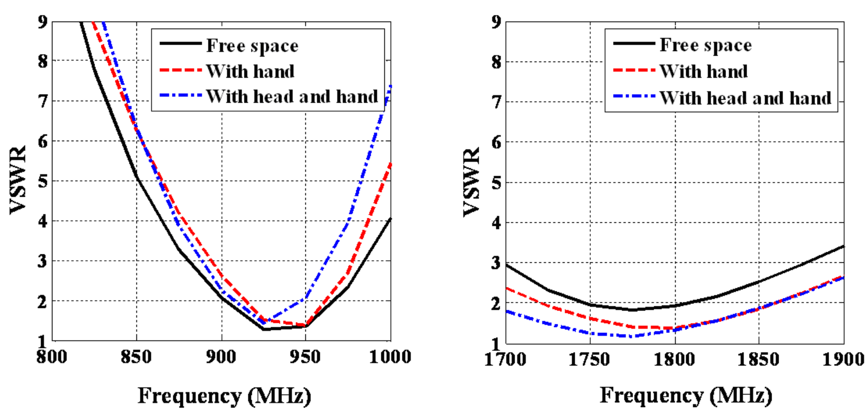
5.1. Structure of the Antennas

Fig. 4 illustrates a dual band helical antenna radiating above a conducting box. Geometry of the antenna has been taken from [26]. This antenna is fed by a 50 Ω coaxial line. Diameter of the outer conductor and length of the coaxial line are 5.2 mm and 8 mm, respectively. Dimensions of the helix are optimized to obtain the minimum VSWR over the GSM and DCS frequency bands. The optimized helix is 19.14 mm long and has a diameter of 6.6 mm. The first 3.25 turns have a pitch of 4 mm, followed by 4.7 turns with a pitch of 1.2 mm.

Fig. 5 demonstrates detailed model of a dual band PIFA antenna placed in the back of a handset. To achieve the necessary bandwidth, the radiating part of PIFA is placed at a distance of 9 mm from the ground plane. General structure of the antenna shown in Fig. 5 is taken from [27], however size of the ground plane and antenna dimensions shown in this figure are different from those given in [27]. Dimensions shown in Fig. 5 provide low VSWR at 900 MHz and 1800 MHz.

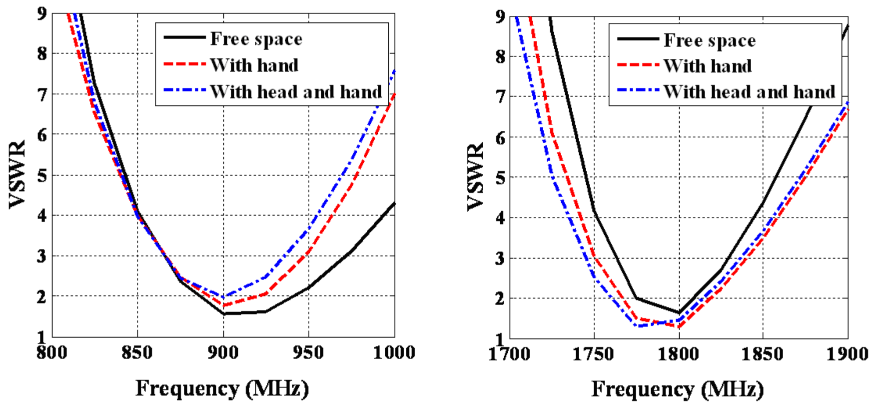
5.2. VSWR

Fig. 6 illustrates the computed VSWR of the helical antenna in the frequency ranges of 800 MHz–1000 MHz and 1700 MHz–1900 MHz. These frequency ranges are wider than the GSM and DCS frequency bands. All VSWR curves are computed in free space, in presence of hand and in presence of head and hand. Position of handset in presence of head and hand has been previously shown in Fig. 2. Fig. 7 presents the computed VSWR of the PIFA antenna. As shown in Figs. 6 and 7, in the lower frequency band, presence of head and hand leads to



(a) (b)

Figure 6. Computed VSWR of the helical antenna in free space and in presence of head and hand. (a) 800 MHz–1000 MHz. (b) 1700 MHz–1900 MHz.



(a) (b)

Figure 7. Computed VSWR of the PIFA antenna in free space and in presence of head and hand. (a) 800 MHz–1000 MHz. (b) 1700 MHz–1900 MHz.

increasing the VSWR, while in the higher frequency band, antenna VSWR is reduced in the presence of head and hand. For PIFA antenna, in both the lower and the higher frequency bands, presence of hand has dominant effect on antenna VSWR.

5.3. Radiation Patterns

Figs. 8 and 9 show the total-power radiation patterns of the previously designed dual band helix and dual band PIFA antenna, respectively. Radiation patterns are computed in free space (figures (a) and (b)), in the presence of hand (figures (c) and (d)) and in the presence of head and hand (figures (e) and (f)). Figures (a), (c) and (e) are corresponding to radiation at 900 MHz and figures (b), (d) and (f) are related to radiation at 1800 MHz.

Radiation of the helical antenna in free space is close to omnidirectional in the x-y plane ($\theta = 90°$). Free space radiation pattern of the PIFA antenna, especially at 900 MHz, is similar to that of the helix. Presence of the user's head has a considerable effect on the radiation pattern of the handset antenna. Radiation pattern of the handset antenna is distorted in the presence of the head. From results shown in Figs. 8 and 9 we can obtain the value of power reduction in a specific direction due to the presence of hand or presence of head and hand. For example for the helical antenna radiating at 900 MHz, presence of the head and hand results in 6.4 dB power reduction in the head direction ($\theta = 90°$ & $\varphi = 90°$) and 1 dB power reduction in

Table 5. Variations in the radiated power of the helix and PIFA antenna in the azimuth plane ($\theta = 90°$) due to the presence of head and hand.

Antenna	At 900 MHz		At 1800 MHz	
	$\varphi = -90°$	$\varphi = 90°$	$\varphi = -90°$	$\varphi = 90°$
Helix	-1.0 dB	-6.4 dB	+1.1dB	-18.0 dB
PIFA	-2.8 dB	-5.1 dB	-0.8 dB	-7.8 dB

the hand direction ($\theta = 90°$ & $\varphi = -90°$). Variations in the radiated power in the above two directions are presented in Table 5 for both the helix and PIFA antenna. For all cases shown in Table 5, especially for the helical antenna, reduction of the radiated power in the head direction is greater than that in the hand direction.

5.4. SAR and Radiation Efficiency

Due to energy absorption in human body, radiated power of a handset antenna is decreased. This decrement of radiated power is characterized by radiation efficiency (η). Antenna radiation efficiency is defined as [5]:

$$\eta = \frac{P_{rad}}{P_{rad} + P_{abs}} = \frac{P_{rad}}{P_{del}} \tag{5}$$

where, P_{abs} is the power absorbed within lossy tissues, P_{rad} is the power radiated to the far field and P_{del} is the power delivered to the antenna. For a handset system increasing the radiation efficiency results in improvement of battery life. Table 6 presents the radiation efficiency of the helix and PIFA antenna in the presence of hand and in the presence of head and hand. As shown in this table, the head and hand absorb about 50% of the power delivered to the handset antenna. Table 6 indicates that in the presence of only hand, radiation efficiency of the helix is greater than that of the PIFA antenna, while in the presence of head and hand, radiation efficiency of the PIFA antenna is greater than that of the helix.

Power absorption in the head is characterized by the SAR quantity. For both the helical and PIFA antennas radiating in the presence of head and hand, the peak spatial average SAR values are shown in Table 7. This table indicates that the SAR in the head induced by a PIFA antenna is about half of that induced by a helical antenna. As pointed out before, standard organizations have set exposure limits in terms of the SAR. According to the US standards, for RF exposure in uncontrolled environments (public exposure) the SAR

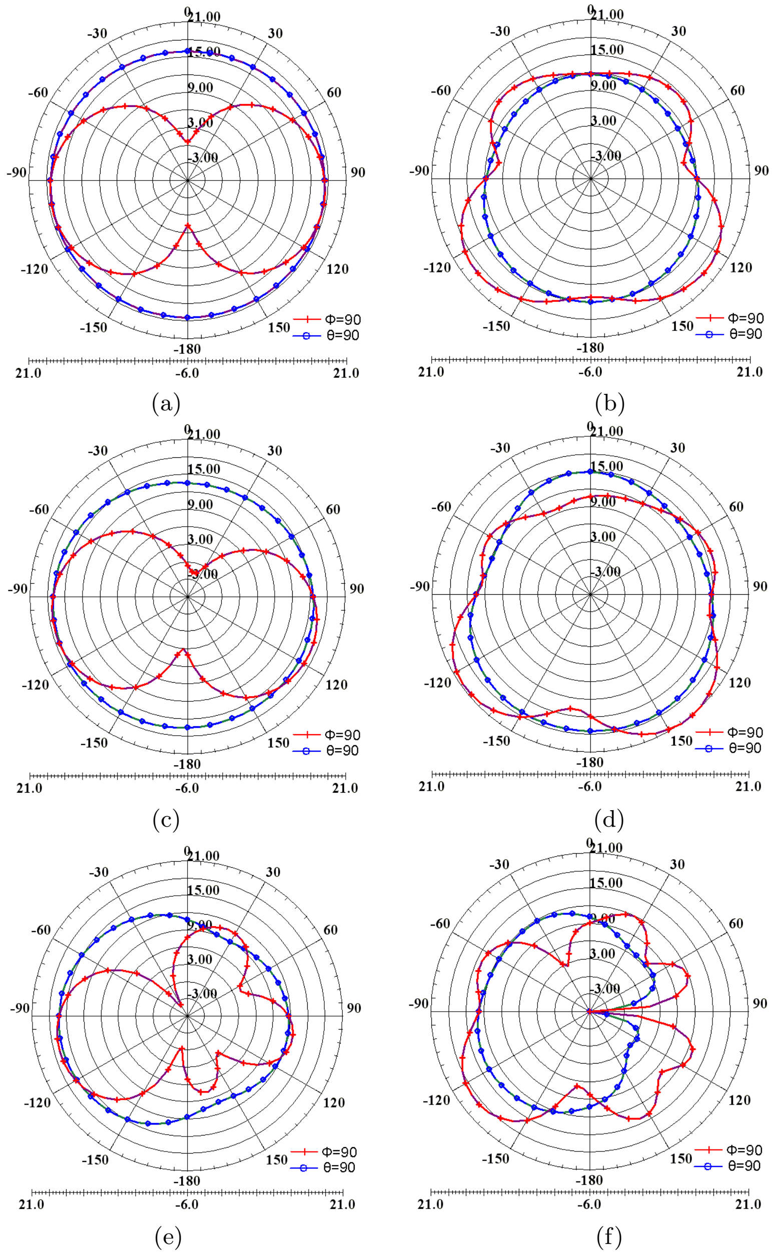


Figure 8. Radiation patterns of the dual band helical antenna. (a), (b) in free space (c), (d) in the presence of hand (e), (f) in the presence of head and hand. Figures (a), (c) and (e) are computed at 900 MHz and the others are obtained at 1800 MHz.

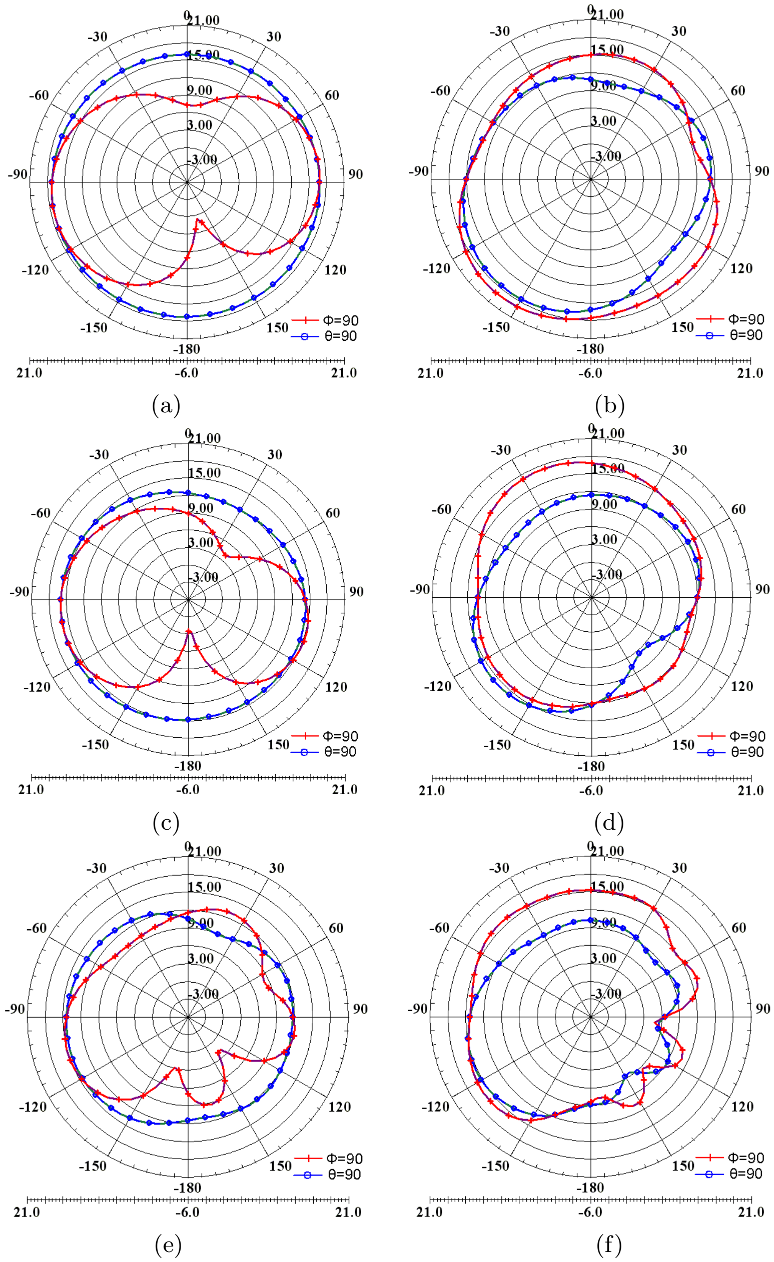


Figure 9. Radiation patterns of the dual band PIFA antenna. (a), (b) in free space (c), (d) in the presence of hand (e), (f) in the presence of head and hand. Figures (a), (c) and (e) are computed at 900 MHz and the others are obtained at 1800 MHz.

Table 6. Radiation efficiency (η) in the presence of hand or in the presence of head and hand.

Antenna	At 900MHz		At 1800MHz	
	Hand	Head and hand	Hand	Head and hand
Helix	82.3%	43.5%	83.4%	53.5%
PIFA	63.9%	43.8%	78.5%	60%

limit is 1.6 W/kg averaged over 1 g of tissue. In Europe, Australia Japan and some other countries, the spatial average SAR limit for public exposure is 2 W/kg averaged over 10 g of tissue [28].

An important characteristic of a handset antenna is its Total Radiated Power (TRP). TRP is defined as the maximum radiated power of the handset antenna to the far field which is limited by the SAR requirement [9]. For example for the PIFA antenna radiating at 900 MHz, when the power delivered to the antenna is 0.25 W, the peak 1-g SAR is 0.714 W/kg (see Table 7); hence the maximum power delivered to the antenna corresponding to 1-g SAR of 1.6 W/kg is 0.56 W. Radiation efficiency of the PIFA antenna at 900 MHz is 43.8% and so the maximum power that this antenna can radiate to the far field, which is defined as the TRP, is 0.245 W.

Table 7. Peak SAR (W/kg) in the head when the handset antenna is radiating in the presence of head and hand ($P_{del} = 0.25$ W).

Antenna	At 900MHz		At 1800MHz	
	1-g SAR	10-g SAR	1-g SAR	10-g SAR
Helix	1.31	0.965	1.81	1.15
PIFA	0.714	0.51	0.772	0.524

TRP provides a good evaluation of the antenna performance from the system point of view [9]. Increasing the TRP of a handset antenna can significantly improve the call performance in a weak signal area. Table 8 presents the TRP of the helix and PIFA antenna in the presence of head and hand at 900 and 1800 MHz. As shown in this table, in both the lower and higher frequency bands, TRP of the PIFA antenna is greater than that of the helix.

Table 8. Total radiated power (W) of the handset antenna in the presence of head and hand.

Antenna	for 1-g SAR of 1.6 W/kg		for 10-g SAR of 2 W/kg	
	900MHz	1800MHz	900MHz	1800MHz
Helix	0.133	0.118	0.225	0.233
PIFA	0.245	0.311	0.429	0.573

6. CONCLUSIONS

A comprehensive study has been presented on the performance of a dual band PIFA and a dual band helical antenna designed for operating in GSM900 and DCS1800 systems. For both antennas, VSWR and radiation patterns have been computed in free space and in the presence of head and hand.

Presence of the head has a considerable effect on the radiation pattern of the handset antenna especially in the head direction. In this direction, reduction of radiated power for the helical antenna is greater than that for the PIFA antenna. Head and hand absorb about 50% of the power delivered to the handset antenna. In the presence of only hand, radiation efficiency of the helix is greater than that of the PIFA antenna, while in the presence of head and hand, the PIFA antenna has greater radiation efficiency.

To determine which handset antenna has less health hazard, the SAR quantity has been computed in the head. It has been shown that the peak average SAR in the head induced by a PIFA antenna is about half of that induced by a helical antenna. Total Radiated Power (TRP) is a parameter that can be used for evaluating the performance of a handset antenna. The obtained results indicate that in both the lower and higher frequency bands, TRP of the PIFA antenna is greater than that of the helix.

REFERENCES

1. ICNIRP (International Commission on Non-Ionizing Radiation), "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," *Health Physics*, Vol. 74, 494–522, 1988.
2. IEEE Std C95.1(tm)-2005, IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz, IEEE, New York, 2005.
3. Yoshida, K., A. Hirata, Z. Kawasaki, and T. Shiozawa, "Human

head modeling for handset antenna design at 5 GHz band," *Journal of Electromagnetic Waves and Application*, Vol. 19, No. 3, 401–411, 2005.

4. Kiminami, K., A. Hirata, Y. Horii, and T. Shiozawa, "A Study on human body modeling for the mobile terminal antenna design at 400 MHz band," *Journal of Electromagnetic Waves and Application*, Vol. 19, No. 5, 671–687, 2005.
5. Jensen, M. A. and Y. Rahamat-Samii, "EM interaction of handset antennas and a human in personal communication," *Proceeding of the IEEE*, Vol. 83, No. 1, 7–17, January 1995.
6. Yioultsis, T. V., T. I. Kosmanis, E. P. Kosmidou, T. T. Zygiridis, N. V. Kantartzis, T. D. Xenos, and T. D. Tsiboukis, "A comparative study of the biological effects of various mobile phone and wireless LAN antennas," *IEEE Trans. Magnetics*, Vol. 38, No. 3, 777–780, 2002.
7. Saraereh, O. A., M. Jayawadene, P. McEvoy, and J. C. Vardaxoglou, "Simulation and experimental SAR and efficiency study for a dual-band PIFA handset antenna (GSM 900/DCS 1800) at varied distances from a phantom head," *Technical Seminar on Antenna Measurements and SAR (AMS)*, 5–8, 2004.
8. Jin, M., Z. Ying, and S. He, "The impact of mobile shell materials on SAR," *Asia-Pacific Microwave Conference Proceedings*, Vol. 5, 2005.
9. Li, Z. and Y. Rahmat-Samii, "SAR in PIFA handset antenna designs: an overall system perspective," *IEEE Antennas and Propagation Society International Symposium*, Vol. 2B, 784–787, 2005.
10. Kildal, P. S. and C. Carlson, "Comparison between head losses of 20 phones with external and built-in antennas measured in reverberation chamber," *IEEE Antennas and Propagation Society International Symposium*, Vol. 1, 436–439, 2002.
11. Kouveliotis, N. K., S. C. Panagiotou, P. K. Varlamos, and C. N. Capsalis, "Theoritical approach of the interaction between a human head model and a mobile handset helical antenna using numerical methods," *Progress In Electromagnetics Research*, PIER 65, 309–327, 2006.
12. Popović, M., Q. Han, and H. Kanj, "A parallel study of SAR levels in head tissues for three antennas used in cellular telephones: monopole, helix and patch," *Springer Earth and Environmental Science*, Vol. 25, No. 2–4, 215–221, December 2005.
13. Ebrahimi-Ganjeh, M. A. and A. R. Attari, "Calculation of Specific Absorption Rate (SAR) and studying the radiation performance

of the helical antenna, in presence of head and hand model for 900 MHz," presented in *15th Iranian Conference on Electrical Engineering (ICEE2007)*, Tehran, Iran, May 15–17, 2007.

14. Kuo, L.-C., Y.-C. Kan, and H.-R. Chuang, "Analysis of a 900/1800-MHz dual-band gap loop antenna on a handset with proximate head and hand model," *Journal of Electromagnetic Waves and Application*, Vol. 21, No. 1, 107–122, 2007.
15. IEEE Std 1528TM-2003, IEEE recommended practice for determining the peak spatial-average Specific Absorption Rate (SAR) in the human head from wireless communications devices: measurement techniques, IEEE, New York, 2003.
16. Adair, E. R. and R. C. Peterson, "Biological effects of radio-frequency/microwave radiation," *IEEE Trans. MTT*, Vol. 50, No. 3, 953–961, 2002.
17. Stevens, N. and L. Martens, "Comparison of averaging procedures for SAR distributions at 900 and 1800 MHz," *IEEE, Trans. MTT*, Vol. 48, No. 11, 2180–2184, 2000.
18. Vorst, A. V., A. Rosen, and Y. Kotsuka, *RF/Microwave Interaction with Biological Tissues*, John Wiley, 2006.
19. Ibrahiem, A. and C. Dale, "Analysis of the temperature increase linked to the power induced by RF source," *Progress In Electromagnetics Research*, PIER 52, 23–46, 2005.
20. Gabriel, C., S. Gabriely, and E. Corthout, "The dielectric properties of biological tissues: I. Literature survey," *Phys. Med. Biol.*, Vol. 41, 2231–2249, 1996.
21. Gabriel, C., "Compilation of the dielectric properties of body tissues at RF and microwave frequencies," Armstrong Lab., Brooks Air Force Base, TX, Brooks Air Force Base Tech. Rep. AL/OE-TR-1996-0037, June 1996.
22. Gandhi, O. P., G. Lazzi, and C. M. Furse, "Electromagnetic absorption in the human head and neck for mobile telephones at 835 MHz and 1900 MHz," *IEEE Trans. MTT*, Vol. 44, No. 10, 1884–1897, 1996.
23. Kang, X. K., L. W. Li, M. S. Leong, and P. S. Kooi, "A spheroidal vector wave function analysis of field and SAR distributions in a dielectric prolate spheroidal human head model," *Progress In Electromagnetics Research*, PIER 22, 149–179, 1999.
24. Francavilla, M., A. Schiavoni, P. bertotto, and G. Richiardi, "Effect of hand on cellular phone radiation," *IEE Proc. Microw. Antennas Propag.*, Vol. 148, No. 4, 2001.

25. Yu, Q. and O. P. Gandhi, "An automated SAR measurement system for compliance testing of personal wireless devices," *IEEE Trans. EMC*, Vol. 41, No. 3, 234–244, 1999.
26. Pisa, S., M. Cavagnaro, V. Lopresto, E. Piuzzi, G. A. Lovisolo, and P. Bernardi, "A procedure to develop realistic numerical models of cellular phones for an accurate evaluation of SAR distribution in the human head," *IEEE Trans. MTT*, Vol. 53, No. 4, 1256–1265, 2005.
27. Abedin, M. F. and M. Ali, "Modifying the ground plane and its effect on planar inverted-F antennas (PIFA) for mobile phone handsets," *IEEE Antennas and Wireless Propag. Letters*, Vol. 2, 226–229, 2003.
28. Chen, Z. N., *Antennas for Portable Devices*, Wiley, 2007.