# Analysis of SAR reduction of mobile phones in heterogeneous media

M. Haridim, B.Levin, Z. Ibragimov, M. Bank

***Abstract*** - The mutual effect of symmetrical electric dipoles located in the near region of each other is considered. The problem is solved with due account of the space heterogeneity. The results are applied to the compensation method for losses reduction in head of phone user. The cellular phone antennas PIFA and MB are compared with each other. The SAR reduction ability combined with the compact size and high gain characteristics of the MB antenna make it a promising candidate for compact and safe cellular handset applications. It is shown that the use of linear array of additional radiators, instead of a single auxiliary radiator is an effective method for increasing the dark spot dimensions.

***Keywords*** – MB antenna, PIFA, Compensation method, Mobile antennas, Mutual coupling, SAR.

## I. INTRODUCTION

Proximity of a transmitting antenna to vulnerable devices or objects may induce damage both in terms of proper operation of such devices and in terms of physical damage. A particular example is mobile telephones placed near the user's head during use. Besides possible health problems, the antenna proximity to user's head may distort its radiation pattern. Methods for reducing the radiation exposure from the phone antenna often lead to further serious distortion of the pattern in horizontal plane, and hence to degradation of the communication link performance. Therefore, it is very important to ensure that when reducing irradiation on an object in the near region, the field magnitude at the far region is not changed, and hence the quality of communication link is preserved.

Creation of a weak field area (called hereafter dark spot) in a desired place around a vulnerable device is an effective solution for various electromagnetic compatibility (EMC) problems. Such method can be effectively applied to protection of mobile phone users, where the dark spot is created in the near field region. A key point in the evaluation of such method is its ability to preserve the antenna's transmitting characteristics, such as radiation pattern, matching, and efficiency. A new method of decreasing the head irradiation, called the compensation method, based on utilization of an auxiliary antenna, was first proposed in [1]. In accordance with this method the auxiliary antenna is placed between the user's head and the main radiator, and excited approximately in anti-phase to it. Consequently the radiators' fields will cancel each other at some point inside the head, and around this point an area of a weak field will be created.

The currents and the fields of antennas used in the compensation method are calculated. Calculations are based on the theory of folded dipoles. The mutual effect of symmetrical electric dipoles located in the near region of each other is considered. The problem is solved with due account of the space heterogeneity. In the article it is shown that in the calculation of the irradiation reduction factor in a given area inside a heterogeneous medium one can use a simple model of field in a homogeneous medium with an equivalent permittivity.

The results are applied to the compensation method for losses reduction in head of phone user, in the case of use of antennas PIFA and MB in a cellular phone. The former antenna is widely used in nowadays mobile handsets, and the latter is an emerging printed antenna with promising characteristics for cellular handset applications, which exhibits superior performance relative to the PIFA. It is shown that the compact size and high characteristics of the MB antenna make it a promising candidate for compact and safe cellular handset applications.

The simulation results show that when antenna MB and compensation method are used instead of PIFA the total SAR decreases by 15.5 dB, and the maximal local SAR decreases by 16.9 dB.

In the article it is shown also that the use of a linear array of additional radiators instead of a single one can effectively increase the dark spot dimensions.

## II. COMPENSATION METHOD

The compensation method permits to reduce the Specific Absorption Rate (SAR) in the user's head, without distorting the antenna pattern in the horizontal plane [2]-[7]. It has been shown that it is possible to achieve compensation of antennas' fields, even when the auxiliary antenna is located very close to the main antenna.

The irradiation level in any part of the user's body can be evaluated by the loss power dissipated in this part, given by the integral $P = \int_{(V)} |E|^2 \sigma dv$ , where $E$ is the electric field strength, $\sigma$ is the tissue conductivity, and $V$ is the volume of that part. In order to calculate this integral, it is necessary to determine the field magnitude at each point inside volume $V$, which corresponds to the antennas near field. Obviously for protection of the user's head the amount of heat losses, particularly in the most sensitive tissues and organs, must be minimized.

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In this work we focus on the impact of the heterogeneous nature of the near field region in the case of a system of two antennas closely spaced in the vicinity of the human head. For this purpose we first developed a method of field calculation in a heterogeneous medium and applied it to the case of two antennas located in the near field of each other in a heterogeneous medium.

The field compensation method for creation of a weak field area near a transmitting antenna provides a generic approach for reducing irradiation of mobile phone user's body, especially his head, without distorting the antenna's pattern in the horizontal plane. We apply the compensation method to different antenna types, namely PIFA, which is widely used in compact cellular handsets, and the so-called MB antenna [8], which has been recently proposed for handset applications. Comparative results based on simulations by the CST Microwave Studio are presented.

The used calculation method permits to determine the shape and dimensions of the weak-field area and to plot the dark spot boundaries in the horizontal plane for different coordinates of the radiators placement points and the compensation point. Moreover, it makes possible field calculation also when two or a multitude of auxiliary antennas are used (instead of a single additional radiator) in order to enlarge the dark spot.

## III. The Impact of Medium Heterogeneity

The calculation of the field magnitude in the vicinity of an antenna becomes complicated in case of a heterogeneous medium surrounding the antenna. Examples include mobile phones such as the cellular phone handsets. The relative permittivity $\varepsilon_r$ of human body differs from that of the free space and has different magnitudes in different tissues. In order to estimate the amount of heat dissipated in the user's body, one must find the field strength inside the human body, which at cellular frequencies is created in the antenna's near region.

We'll now consider the influence of the user's head as it is the most vulnerable object and closest to the handset. We model the human head as an ellipsoid elongated along a vertical axis (a sphere, in the simplest case), and assume that a linear antenna is tangent to the ellipsoid at the center of its side surface, as shown in Fig. 1.

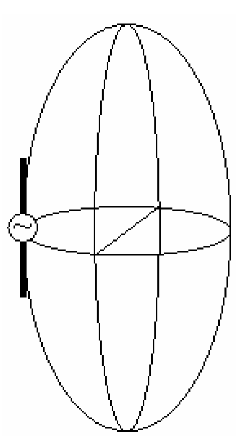


Fig. 1. Model of head with antenna

For field calculations in the first-order approximation, one may assume that the radiator is located in a plane at the interface of two half spaces, namely free space ($\varepsilon_r = 1$), and a dielectric medium with $\varepsilon_r \neq 1$. In this case the EM problem reduces to calculation of the field produced by a linear radiator located at the boundary of two media.

The problem of electrostatic field calculations in a heterogeneous (or more exactly, piecewise-homogenous) medium is considered in [9]. Such problem particularly arises, if an isolated wire is located at the boundary of two media, for instance, air and a dielectric with $\varepsilon_r \neq 1$ as shown in Fig. 2. Here, the wire is of circular cross-section and it is assumed that $\varepsilon_r$ in each region is uniform. The method for calculation of the electrostatic field can be used for solving other problems. According to the correspondence principle, one can use the known solution for the electric field of linear charges to find the magnetic field produced by electric currents, provided the currents and charges are equally distributed [10]. An alternating linear current would produce a quasi-stationary electromagnetic field with a similar structure. Since the antenna field in a near region has a quasi-stationary character, the analogy with the electrostatic problem permits to reduce the field calculations in a piecewise-homogeneous medium to the field calculation in a homogeneous medium.

The solution of the electrostatic problem (see Fig. 3) is based on the fact that the potential on the wire's surface is constant and at large distances from the wire the potential is the same in all directions. Hence, we may assume that the equipotential lines are circles centered at the origin, and that the equipotential surfaces are cylindrical. This way, the field in the piecewise-homogenous medium coincides with the field in a homogenous medium of an equivalent permittivity given by

$$\varepsilon_e = (1 + \varepsilon_r)/2. \quad (1)$$

If the permittivity in both media is uniform, we may assume that also the equivalent permittivity is uniform. It means that the field in the piecewise-homogenous medium will coincide with the field in a homogenous medium of permittivity $\varepsilon_e$.

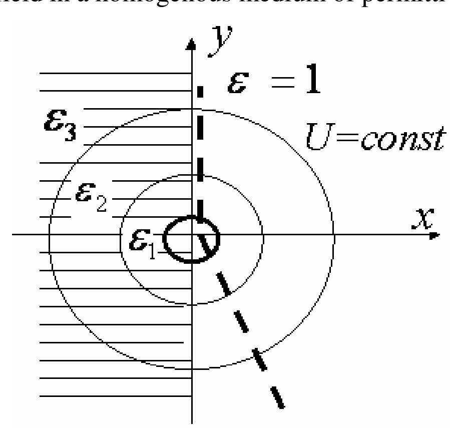



Fig. 2. Electrostatic field of a charge in a heterogeneous medium

Then, starting from the correspondence principle, one can show that the EM field components of a linear radiator, which is located at the boundary of two media, differ from the field components in the air only by the value of permittivity.

The permittivity of brain, muscles and skin are similar and, on average, equal to 50, and hence we may use an equivalent permittivity $\varepsilon_e$= 25 for the whole region. Thus, the solution for the problem of field calculation in case of an antenna located near the head can be obtained by field calculation in a homogenous medium with $\varepsilon_e$=25. This method can be applied also to the case of the compensation method when using a few additional antennas (an antenna array instead of a single antenna) are used in order to increase the irradiation reduction factor.

In the case of a small distance (compared to the wavelength) between the antenna and the head, one can consider the field in the equivalent homogenous medium as the first approximation to the field inside the head. In this case, the field close to the antenna is slightly different from the field in the absence of the head. However, since the field is inversely proportional to $\varepsilon_r$, the field magnitude sharply changes at the boundary between the two media and its components inside the head are much weaker than those outside the head.

The change of a heterogeneous medium by an equivalent homogeneous medium substantially simplifies and facilitates the field calculation problem. The obtained results are validated by comparative studies using CST simulations.

## IV. LINEAR RADIATORS IN THE NEAR FIELD REGION

The Hertz dipole is an analogue of a linear radiator only in the far region. In the near region, on the other hand, the field components of a Hertz dipole differ from those of a linear radiator of finite length. Therefore, we shell consider dipoles and monopoles of finite size as linear antennas. Another problem is that the Hertz dipole does not allow for considering mutual coupling effects, as its length is much smaller than the radiation wavelength. Therefore, in order to achieve accurate results, one should use linear antennas of finite length.

The compensation method is a general approach for reducing the user's head irradiation. In this method, an auxiliary radiator is located in the plane passing through the head center and the main radiator of the transmitter, between the head and the main radiator, and is exited approximately in anti-phase relative to the main radiator. In this manner the radiators' fields will compensate each other in some point inside the head, and around this point an area of a weak field (a dark spot) is created.

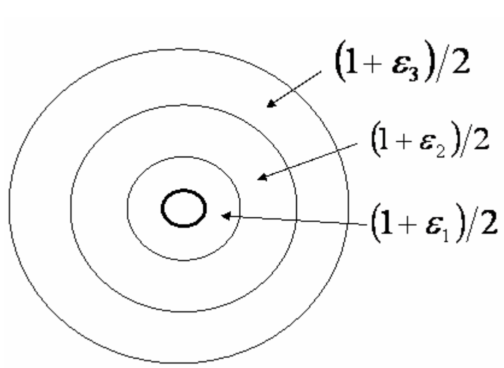



Fig. 3. Equivalent homogenous medium for the heterogeneous medium of Fig. 2

Let us find the current and the input impedance of a radiator, located in the near region of a neighboring radiator. Fig. 4 shows the equivalent circuit for the case when an electromotive force (emf) is connected at the input of the first radiator, and the second radiator is not active. Here, the radiators are monopoles of finite lengths, $R_1$ is the output impedance of the generator feeding the first antenna, $R_2$ is the impedance of the generator feeding the second antenna, which is not excited. Generally, the generators have equal impedances, i.e. $R_1 = R_2 = R$, and these impedances are measured at the input of generators or at the input of cables leading to the generators.

The mutual coupling between antennas can be evaluated by the equivalent circuit of Fig. 5 [3]. It has been shown that the input admittances of the radiators are

$$Y_{A1} = \frac{J_{A1}}{e_1} = Y_1 + Y_2 + \frac{e_2}{e_1}\left(Y_2 - Y_1\right),$$

$$Y_{A2} = \frac{J_{A2}}{e_2} = Y_1 + Y_2 + \frac{e_1}{e_2}\left(Y_2 - Y_1\right), \qquad (2)$$

where

$$Y_1 = 1/\left(-jW_l ctgkL_2 + 2R\right) \qquad (3)$$

is the input admittance of a two-wire line whose length is equal to the length of the shorter radiator $L_2$, and the wave impedance is $W_l = 120\ln(b/a)$, where $b$ is the distance

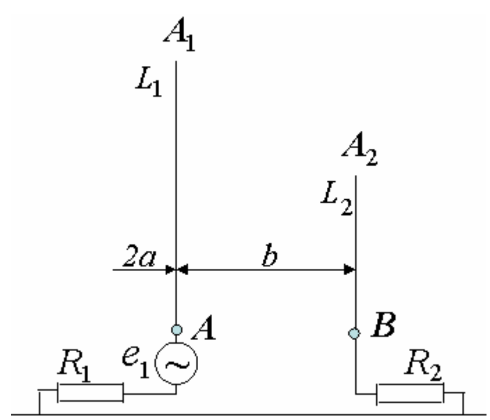



Fig. 4. Two radiators in close proximity (near region)

between the wires, and $a$ is the radius of each wire. The admittance $Y_2$ is equal to

$$Y_2 = 1/\left[4Z_m\left(L_1, a_e\right) + 2R\right], \qquad (4)$$

where $Z_m = Z_m\left(L_1, a_e\right)$ is the input impedance of a monopole, whose length is equal to the length of the longer radiator $L_1$, and $a_e$ is its equivalent radius, which is equal to $a$ at the upper section of the monopole $(L_2 \le z \le L_1)$ and $a_e = \sqrt{ab}$ at its lower section $(0 \le z \le L_2)$.

The ratio between the driving currents (at their bases) of the radiators, which leads to mutual cancelation of their fields in a given point, has been calculated. It has been shown that this ratio is different from the current ratio required in the absence of mutual coupling between the radiators and coincides with it only in particular cases.

As shown, our analysis method for evaluation of the mutual coupling between the radiators is based on the folded dipoles theory. Field calculation results for an assembly of two linear radiators of finite lengths demonstrate that, as expected, the field characteristics are substantially different from those corresponding to the case that Hertz dipoles are used instead of radiators of finite lengths. In particular, the dark spot created by radiators of finite lengths is substantially greater than that produced by Hertz dipoles.

As an example, in Fig. 6 the ratios $\left|E_z/E_{z10}\right|$ and $n = \left|E_z/(BE_{z10})\right|$ at a frequency of 1 GHz are plotted as a function of the distance $\rho$ for three different cases with dimensions (in centimeters): $L_1 = L_2 = 7.5, b = 3,$ $\rho_0 = 1.0; 6.65; 8.0$. The parameter $B$ denotes the ratio between the total field $E_z$ to the field of the main radiator at the sufficiently large distances.

The dark spot boundary is defined by the magnitude of $\rho_n$, at which $n = \left|E_z/(BE_{z10})\right| = n_0$, where $n_0 < 1$ determines the field reduction factor inside the dark spot. In order to find the boundaries of the dark spot in the horizontal plane, one must

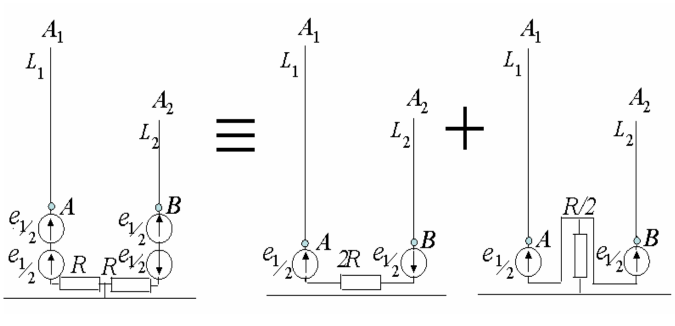



Fig. 5. Equivalent circuits for the antenna system of Fig.4

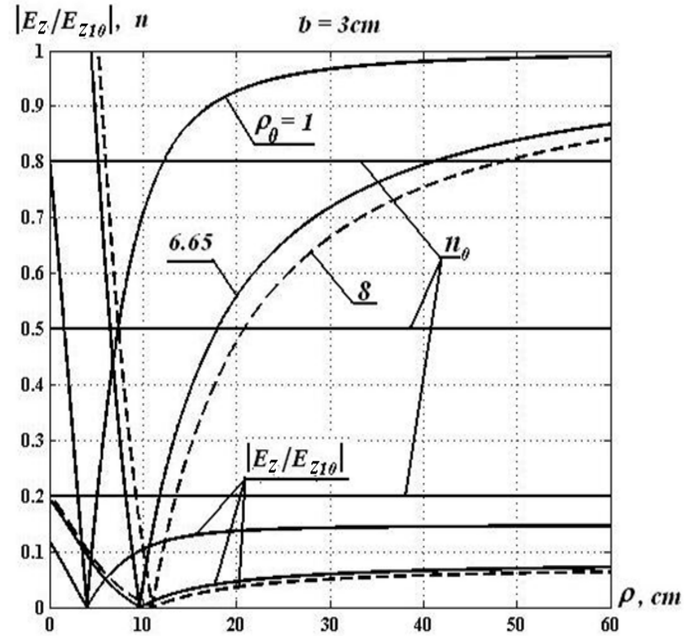



Fig. 6. The fields ratio as a function of the distance $\rho$

determine the magnitude of $\rho_n$ corresponding to different values of $\varphi$. The dark spot boundaries in the horizontal plane ($z = 0$) are plotted in Fig. 7 at the frequency 1 GHz for the scenario of $L_1 = L_2 = 7.5, b = 3,$ $\rho_0 = 6.65$ and 9.3 and different values of $n_0$.

The compensation method may be used also for creating dark spots at a desired height above the system axis [5].

## V. CHARACTERISTICS OF PIFA AND MB ANTENNAS AND SIMULATION RESULTS

The compensation method is applied to PIFA and the MB antenna. PIFA is widely used in cellular handsets and the recently proposed MB antenna seems to be well suitable for compact handsets. The main characteristics of both PIFA and the MB antenna are presented in Table 1. The characteristics of the MB antenna were studied by CST simulations. As seen from Table 1, the MB antenna has superior performances over PIFA.

The input characteristics (parameter S) of the antenna PIFA and the MB antenna as a function of frequency $f$ are given in Fig. 8. As seen from this Figure the MB antenna has three frequency bands.

Table 1. Main characteristics of the MB antenna and PIFA

| Antenna type | Frequency, GHz | Total efficiency, dB | Directivity, dB | Gain, dB |
|---|---|---|---|---|
| MB | 1.305 | -0.0139 | 4.384 | 4.384 |
| PIFA | 0.9 | -2.094 | 2,148 | 1.924 |

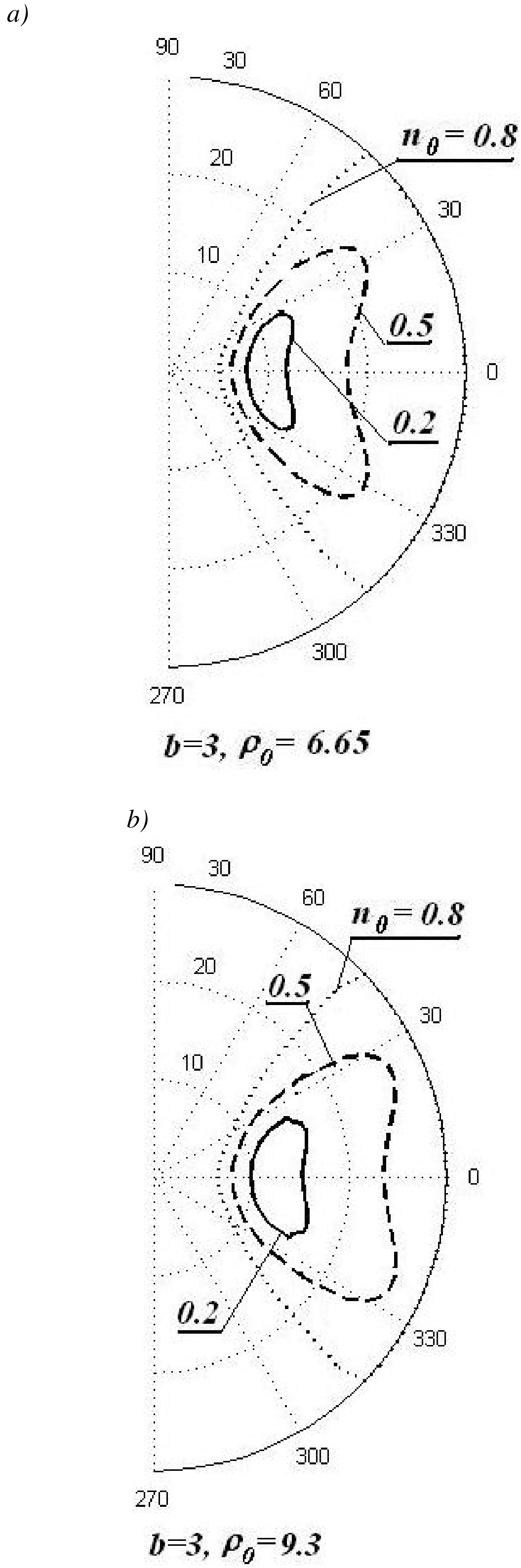



Fig. 7. The dark spot boundaries

Simulation results for the far field performance, and gain of the antennas are shown, respectively, in Fig. 9, and 10. As it can be seen in Fig. 9, the MB antenna has less radiation in the vertical direction. In Fig. 11 the spatial distribution of local SAR in the user's head is shown under application of the compensation method. Fig. 11*a* corresponds to the case of two MB antennas, and in Fig. 11*b* two PIFAs are used.

Table 2 summarizes the results of the compensation method applying. In this Table $E_{max}$ is the maximum field strength at distance 5 m, $E$ is the field strength inside in the dark spot. The total and maximum local SAR are also presented in this Table. The obtained values are compared to those obtained in the case of a single (main) antenna, i.e. without the auxiliary antenna. As seen from Table 2, the MB antenna allows for a substantial reduction of the SAR value in the user's head.

Table 3 compares the SAR reduction performance of the compensation method in the cases of the MB antenna and PIFA. As it can be seen from this Table, in the case of the MB antenna the total SAR is decreased by 15.5 dB, and the maximum SAR is reduced by 16.9 dB. The corresponding values for PIFA are 4.4dB for total SAR and 9dB for maximum SAR level.

Table 2. Fields and SAR values

| Type and number of antennas | $E_{max}$ at far region | $E$ at near region | maximum local SAR | total SAR |
|---|---|---|---|---|
| MB, one | -56.22 | 218 | 2.8□$10^{-4}$ | 2.08□$10^{-5}$ |
| PIFA, one | -56.19 | 2135.3 | 2.69□$10^{-3}$ | 3.73□$10^{-5}$ |
| MB, two | -59.8 | 105 | 5.53□$10^{-5}$ | 1.05□$10^{-6}$ |
| PIFA, two | -60.42 | 492.8 | 3.37□$10^{-4}$ | 1.36□$10^{-5}$ |

Table 3. SAR reduction for the MB antenna and PIFA

| Type and number of antennas | Gain, dB | maximum local SAR,dB | total SAR,dB |
|---|---|---|---|
| Single MB | 4.384 | -9.8 | -2.5 |
| Single PIFA | 1.924 | 0 | 0 |
| Two MBs | | -16.9 | -15.5 |
| Two PIFAs | | -9 | -4.4 |

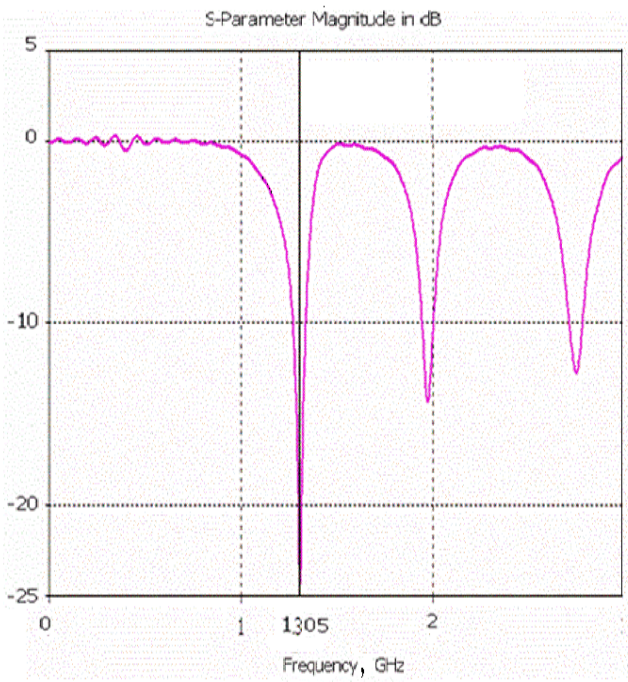
This result combined with small size and high gain of the MB antenna makes it very attractive for use in compact handsets.

The MB antenna may be designed for operating in three frequency bands. The input characteristics of the antenna MB (as the main antenna in the compensation method's structure) in three bands are given in Fig. 12.

## VI. TWO ADDITIONAL RADIATORS

Obviously, using a multitude of auxiliary antennas located in different directions relative to the main radiator permits to create a multitude of dark spots in these directions. To increase the dark spot dimensions is a more complex problem. It may be solved by using of two additional radiators. Here, we present a method for increasing the dark spot dimensions using only two or three auxiliary radiators, as depicted in Fig 13.

*a)*

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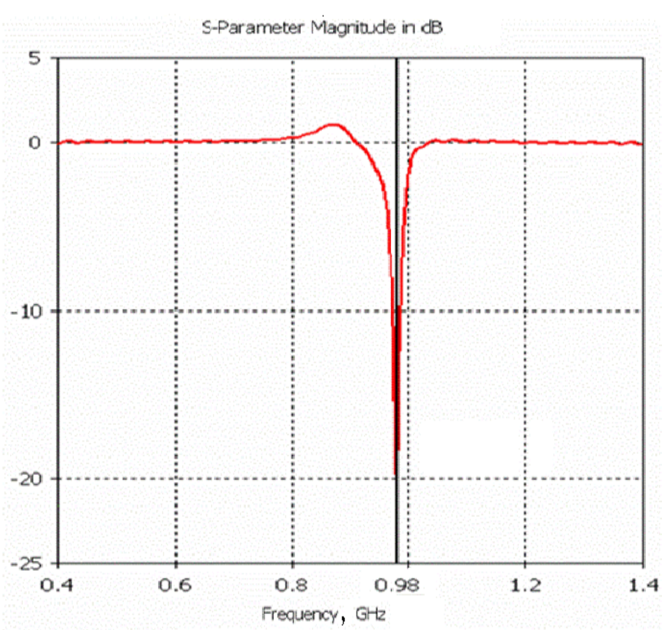
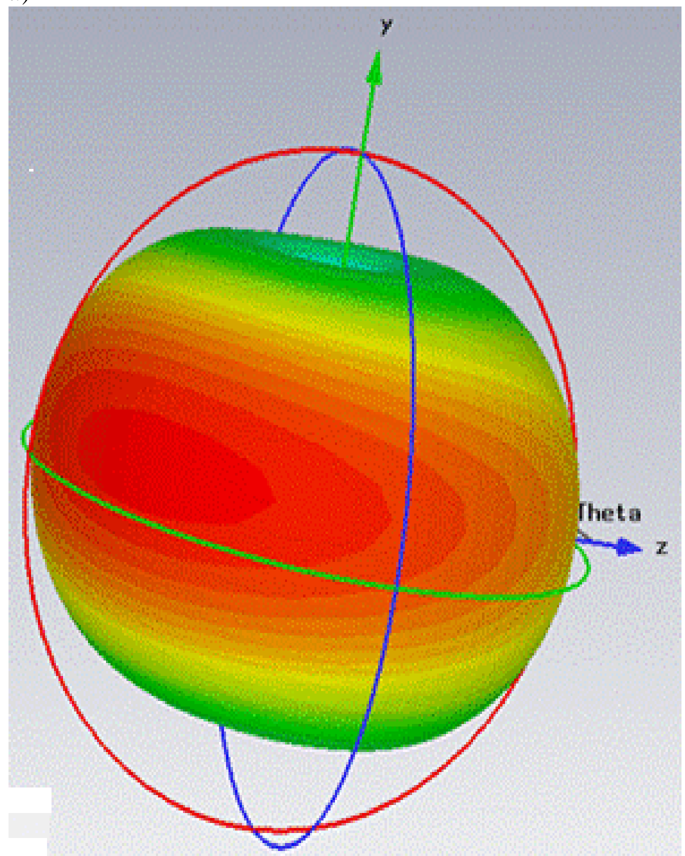



Fig. 8. Input characteristics of the MB antenna (*a*) and the PIFA (*b*)

*a)*

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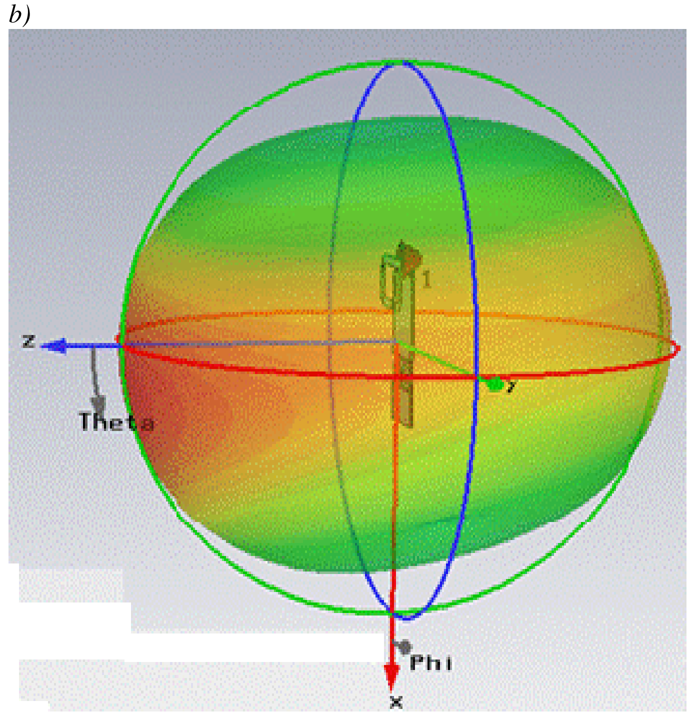


Fig. 9. The far fields of the MB antenna (*a*) and the PIFA (b)

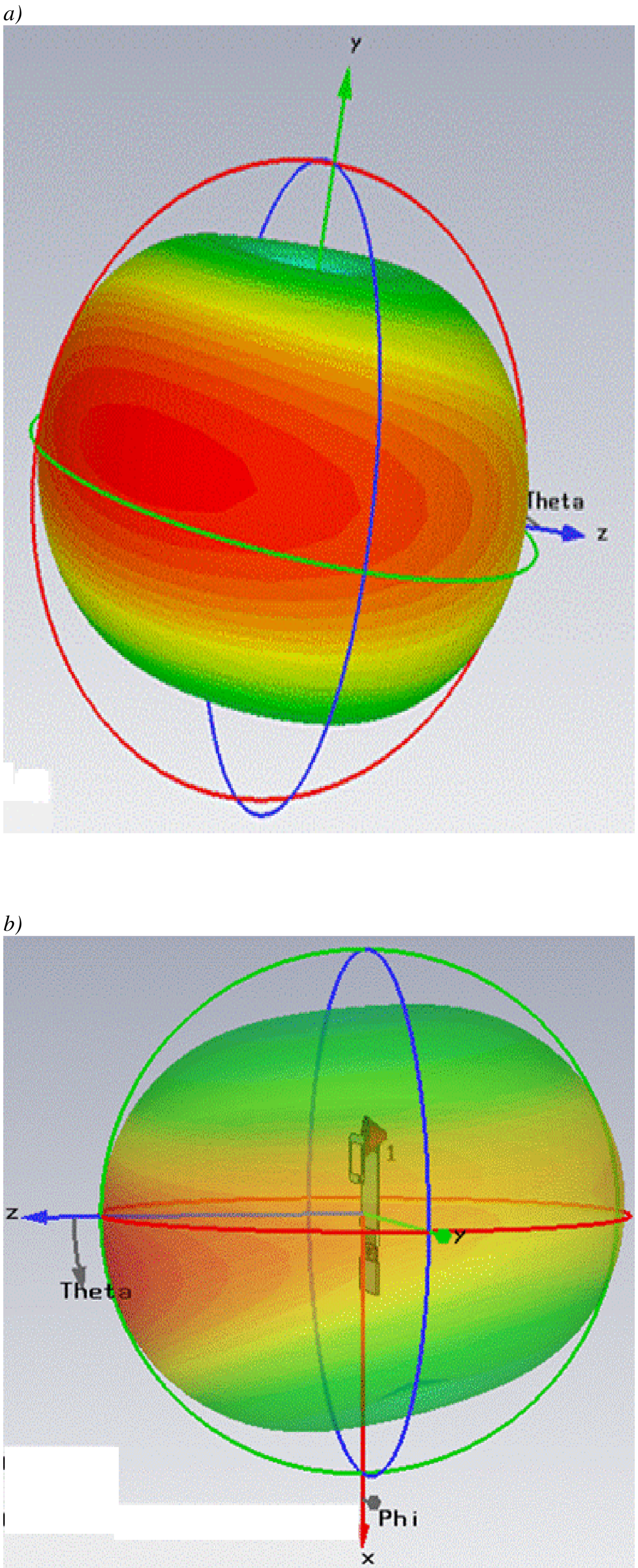


Fig. 10. Gains of the MB antenna (*a*) and the PIFA (*b*)

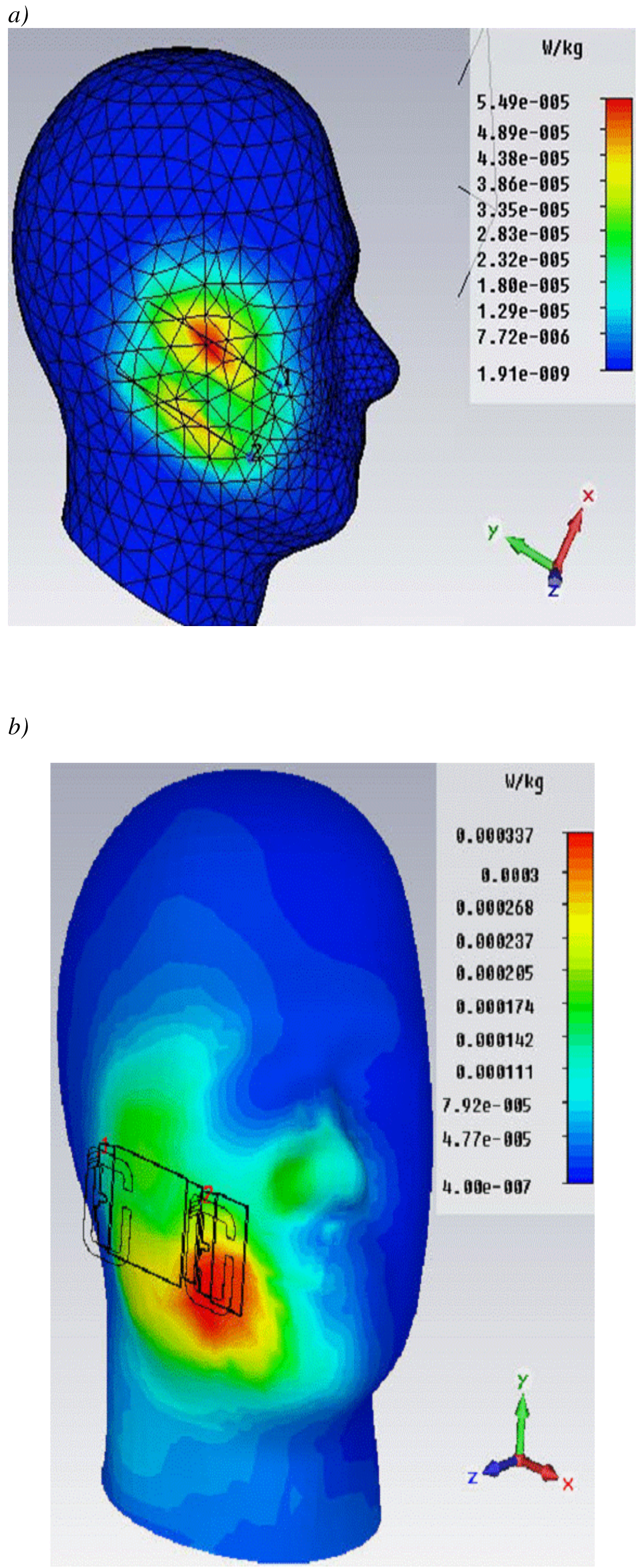


Fig. 11. The spatial distribution of local SAR using the compensation method: the MB antenna (*a*) and PIFA (*b*)

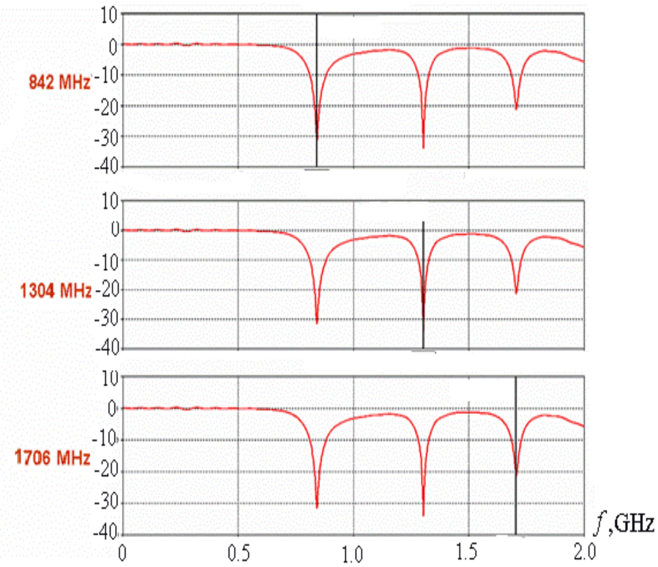


Fig. 12. Input characteristics of the MB antenna in three frequency bands

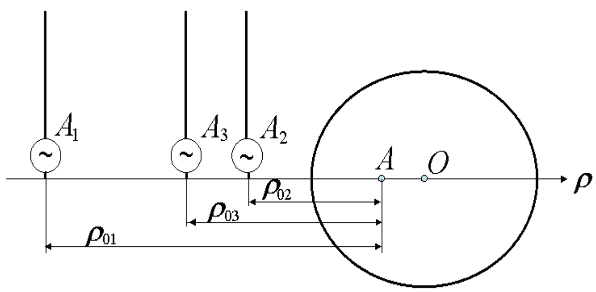


Fig. 13. Radiators placement with two additional radiators

In Fig. 13, $A_1$ is the main radiator, $A_2$ and $A_3$ are the auxiliary radiators, and $A$ is the compensation point. As it is seen in this Figure, the radiators are vertical monopoles of equal length $L$. The feed points of the radiators and the compensation point are all placed along the horizontal straight line passing through the head center $O$. At the compensation point the total field must vanish

$$E_z = E_{z1} + E_{z2} + E_{z3} = 0. \qquad (5)$$

The component $E_{zi}$ of the electric field vector of radiator $i$ located in a homogeneous medium with a relative permittivity of $\varepsilon_r$ is equal to

$$E_{zi} = -j\frac{30 J_{Ai} F_i(z,\rho_i)}{\varepsilon_r}, \qquad (6)$$

where

$$F_i(z,\rho_i) = \frac{1}{\sin kL}\left[\frac{\exp(-jkR_{i1})}{R_{i1}} + \frac{\exp(-jkR_{i2})}{R_{i2}} - 2\cos kL\frac{\exp(-jkR_{i0})}{R_{i0}}\right], \qquad (7)$$

Here $R_{i1} = \sqrt{(z-L)^2 + \rho_i^2}$ is the distance from the observation point $M$ with coordinates $\rho, \varphi, z$ to the upper end of the monopole, $R_{i2} = \sqrt{(z+L)^2 + \rho_i^2}$ is the distance from point $M$ to the lower end of the monopole's mirror image and $R_{i0} = \sqrt{z^2 + \rho_i^2}$ is the distance from point $M$ to the monopole base. If $M$ coincides with the compensation point $A$, then $z = 0$, and $R_{i1} = R_{i2}, R_{i0} = \rho_{i0}$ ($\rho_{i0}$ is the distance from the base of radiator $i$ to the compensation point). The field of each additional radiator at point $A$ must cancel a part of the main radiator field, e.g. one half of it in the case of two auxiliary radiators and one-third of it in the case of three auxiliary radiators.

The calculation results for the absolute values of singular radiators fields and a total field for $\lambda$=30cm, $L$ =7.5cm, $\rho_{01}$=11cm, $\rho_{02}$=5cm (corresponding to variant 6 of Table 4) are presented in Fig. 14. In Fig. 15 the ratio $n = (B|E_{z1}|)/|E_z|$ as function of $\rho$ is plotted. Here $|E_{z1}|$ is a magnitude of the main radiator field, $|E_z|$ is a magnitude of the total field and $B = |E_z|/|E_{z1}||_{R\to\infty}$ takes account of a possible decrease of the total field in comparison with the main radiator field at distant observation points (this far field decrease requires to increase the transmitter power by a factor of $B$).

The length $\Delta\rho$ of a segment on the $\rho$ axis, in which $n$ is smaller than required level $n_0$ is given in Table 4 for different values of $n_0$, i.e. for different values of a field magnitude decrease at the spot boundary. It is accepted that when two auxiliary antennas are used the driving currents of the three antennas are equal to

$$J_{A2}F_2(0,\rho_{02}) = J_{A3}F_3(0,\rho_{03}) = -J_{A1}F_1(0,\rho_{01})/2.$$

Variants 7 and 8 in Table 4 should be compared with

Table 4. Magnitude of $\Delta\rho$ at various conditions

| Var. | $\rho_{01}$ (cm) | $\rho_{02}$ (cm) | $\rho_{03}$ (cm) | $\rho_{04}$ (cm) | $n_0$ | | |
|---|---|---|---|---|---|---|---|
| | | | | | 0.8 | 0.5 | 0.2 |
| 1 | 1.5 | 1.0 | | | 9.6 | 4.5 | 2.2 |
| 2 | 1.5 | 1.0 | 1.2 | | >50 | 6.1 | 2.5 |
| 3 | 1.5 | 1.0 | 1.4 | | >50 | 11.1 | 3.1 |
| 4 | 2.5 | 1.5 | | | 10.7 | 5.1 | 2.7 |
| 5 | 2.5 | 1.5 | 2.0 | | >50 | 7.5 | 3.2 |
| 6 | 11 | 5 | | | 28.9 | 9.7 | 3.2 |
| 7 | 11 | 5 | 8 | | >50 | 18.8 | 4.9 |
| 8 | 11 | 5 | 7 | 9 | >50 | >50 | 8.6 |

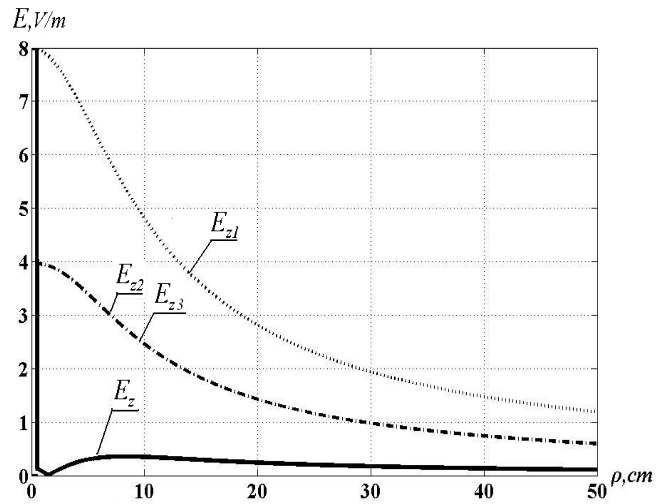


Fig. 14. Radiators fields and total field for the variant 6

variant 6 (one auxiliary antenna) where $J_{A2}F_2(0,\rho_{02}) = -J_{A1}F_1(0,\rho_{01})$. One can see from Table 4 that the second auxiliary radiator allows for a significant increase of the dark spot dimensions.

In the general case, one can replace the two auxiliary radiators by an antenna array. The radiators of the array should be placed along the horizontal straight line passing through the main radiator and the center of the dark spot. This arrangement ensures that no additional null will be created in the horizontal radiation pattern. Otherwise an additional null will be created along the horizontal straight line passing through the main and the auxiliary radiator.

## VII. Conclusions

In conclusion, we have developed a simple method for field calculations in a heterogeneous medium. This method was applied to the case of two antennas in proximity to the human head.

We have applied the field compensation method to the cases of the MB antenna and PIFA antenna. Simulation results show that this method yields efficient SAR reduction in both cases. However, in the case of the MB antennas, the SAR reduction factor is higher by about 10 dB, in terms of total SAR value. As a printed monopole, the MB antenna lends itself well for utilization in cellular handsets, where SAR reduction is of great importance. It is also shown that using a linear array of auxiliary radiators can effectively increase the dark spot dimensions.

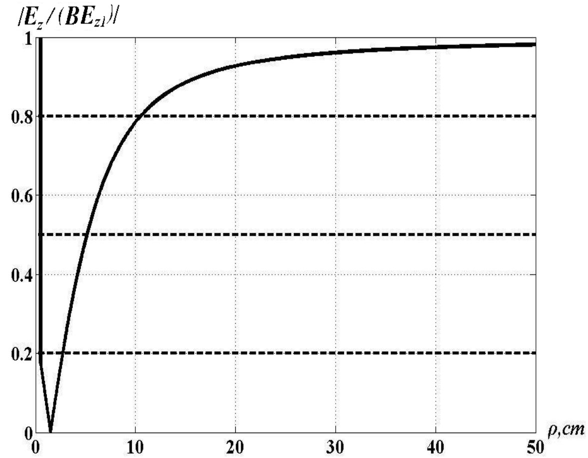


Fig. 15. Dependence of the ratio $n$ on $\rho$ for the variant 6

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