

## **The Development of the Cellular Phone Antenna with a Small Radiation of Human Organism Tissues**

Michael Bank (Kaf Tet Benovember St., 6/8, Ashdod, 77450, Israel, Tel/Fax 972 8 8640565,

E-mail [michaelbank@bezeqint.net](mailto:michaelbank@bezeqint.net)),

Boris Levin (Tlamim St., 5/23, Lod, 71338, Israel, Tel/Fax 972 8 9246996,

E-mail [levinpaker@hotmail.com](mailto:levinpaker@hotmail.com))

**Abstracts** - The method put forward here is to reduce the undesirable irradiation using the auxiliary radiator of low power. Calculations show that an arrangement with an additional radiator reduces irradiation by a factor of three to four. Structure and field magnitude in a far zone preserve their quality of communication with the correspondents (base stations) in all directions.

**Index Terms** - Antenna theory, Biological radiation effects, EMC, Irradiation, Mobile antennas, Telephone equipment, Auxiliary radiator, Irradiation decrease factor.

### **1. Introduction**

One of the basic aims of the EM theory is to create an electromagnetic field with a predetermined structure. In the case under study, a predetermined field structure is to be created near an antenna (radiator). The significance of this goal should be clear. For example, a fundamental electromagnetic problem, regarding compatibility, to a considerable extent, is caused by a mutual effect of radiation sources located at close proximity to each other.

In the vicinity of power radio transmitting centers, field strength is so great that one may become anxious over neighboring citizens health. A dangerous zone radius increases as the wavelength grows. Over VHF range a near region radius is small. However, because of the close proximity of a portable cellular phone to the user's head during a phone conversation sensitive human organs (for example, a brain or eyeball) are in the radiator near field. This causes an irradiation of human organism tissues leading to a health risk [1-4].

In addition, the radiator proximity to user's head distorts an antenna pattern and results in power losses.

It is necessary to reduce the irradiation of human tissue. At the same time, a structure and a field magnitude in a far zone should not change. This is to preserve the quality of communication with the correspondents (base stations) in any direction. The methods of achieving the stated goals are different; however, all of them require investigation of field structure features as well as the above field behavior in near regions of various radiators.

## 2. Known methods

Today, extensive researches are being made on the creation of new antenna types for portable cellular phone [5-13]. Some methods of reducing the interaction level between the phone antenna and the human head are possible. These methods are presented on Table 1, together with methods of antenna pattern deformation reduction.

The first method removes the antenna from the most sensitive part of human tissues. This method is utilized for examples in USA patents 5950116 and 5513318 and also in the international patent WO 9944346. The antennas, which are produced according to this method, are bulky, not aesthetic and also not very practical for use.

The second method is antenna screening or radiation absorption on the human side. Antenna screening was utilized, for instance, in USA patents 5784032, 5826201, 5657386 amongst others. The radiation absorption was utilized in USA patent 5666125. However, in order to shield a users head it is necessary to employ a screen, which is substantially larger in size than a lateral dimension of phone housing. This results in changes in the field magnitude in a far zone. Fig. 1 shows the pattern distortion caused by a screen. For similar reasons, one must reject an absorber application.

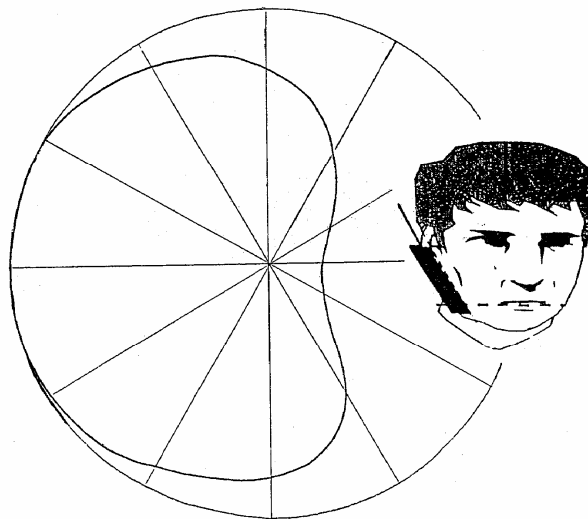


Fig. 1. Antenna pattern distortion.

Therefore, numerous suggestions (patents) based on human head shielding or on a radiation reduction in its direction, are unacceptable.

The third known method is to use the directive antenna with null zone in the given direction. This method is used, for example, in international patent 0876688. This method also degrades the communication quality.

Thus the stated problems are not solvable via the known methods.

In order to attenuate the interaction between the portable cellular phone antenna and the human head, one has to develop an antenna with reduced field strength in near region (a field in the far region must not be changed). One approach is to design an omnidirectional antenna with a field, which is decreased in the near region.

The horizontal magnetic dipole is such antenna. Actually, an electric field strength of an elementary electrical dipole (a Hertz dipole), located vertically along an axis  $z$  ( $\vartheta = 0$ ), is equal (see for example, [14])

$$E_1 = j30klJ \left( 1 + \frac{1}{jkR} - \frac{1}{k^2 R^2} \right) \frac{e^{-jkR}}{R} \sin \vartheta \quad (1)$$

Here  $k$  is the propagation constant,  $l$  is the dipole length and  $J$  is the electrical current along it. The spherical coordinate frame  $(R, \vartheta, \varphi)$  is used.

Table 1. Known methods

1. Decrease of a head irradiation

1.1. Removing the antenna from a sensitive human tissues

Patent of USA N5950116 “Mobile telephone with off-center antenna” (Inventor J.Baro)

International patent WO 9944346 “Reduced radiation in hand” (Inventor O’Badia N.)

Patent of USA N5513383 “Mobile communication terminal having extendable antenna” (Inventor C.A.Tsao)

1.2. Screening and absorption

International patent WO 9747054 “Dual resonance antenna for portable telephone” (Inventor E.A.El-Sharawy)

Patent of USA N5784032 “Compact diversity antenna with weak back near fields” (Inventors R.H.Johnston, L.G.Levesque)

Patent of USA N5826201 “Antenna microwave shield for cellular telephone” (Inventor G.Gratias)

Patent of USA N5657386 “Electromagnetic shield for cellular telephone” (Inventor J.H.Schwanke)

Patent of USA N5666125 “Radiation shielding and range extending antenna assembly” (Inventors N.N.Luxon, K.A.Luxon, R.J.Milelli)

International patent WO 9426000 “Anti-electromagnetic field antenna for cellular telephone” (Inventor C.E.Combest)

1.3. Null zone

International patent WO 0876688 “Directive antenna with null zone”

2. Reduction of antenna pattern deformations

## 2.1. Mechanical methods

Patent of USA N5854970 "Accessory RF unit for hand-held wireless telephone systems"  
(Inventor S.K.Kivela)

## 2.2. Diversity reception

Patent of USA N5337061 "High performance antenna for hand-held and portable equipment"  
(Inventors M.R.Pye, S.A.Williams)

Patent of USA N4710975 "Space diversity reception system having compensation means of multipath effect" (Inventors Y.Okamoto, I.Horikawa, S.Komaki)

International patent WO 0030267 "Cellular phone, flip and hinge" (Inventors T.Fukuda, S.Nakamura, M.Sakuma)

International patent WO 9744911 "Method and device for local elimination or restriction of a radio-frequency radiation field" (Inventors M.Ottelin, H.Ryhaenen).

Electric field strength of an elementary magnetic dipole located horizontally along an axis  $x$  ( $\varphi = 0$ ) is equal

$$E_2 = -j \frac{klJ_M}{4\pi} \left( 1 + \frac{1}{jkR} \right) \frac{e^{-jkR}}{R} \sin \varphi, \quad (2)$$

where  $J_M$  is the magnetic current along the dipole.

Hence, the electrical field strength of a magnetic dipole by contrast to the same field of an electric dipole does not contain the term, which is reciprocal to cube of a distance  $R$  from a radiator. In other words, as the distance  $R$  is reduced, the field of a magnetic dipole increases much more slowly than the field of an electric dipole (Fig. 2). Since the irradiation power (the power, which is absorbed in the human head share adjacent to the telephone) is proportional to  $E^2$ , the thermal losses are

$$P = \int_{(v)} |E|^2 \sigma dv, \quad (3)$$

where  $\sigma$  is the head tissues conductivity and  $V$  is the head volume. Then, if the radiation powers of electric and magnetic dipoles are equal (the fields magnitudes in the far region are the same) the irradiation power of the magnetic dipole is reduced substantially.

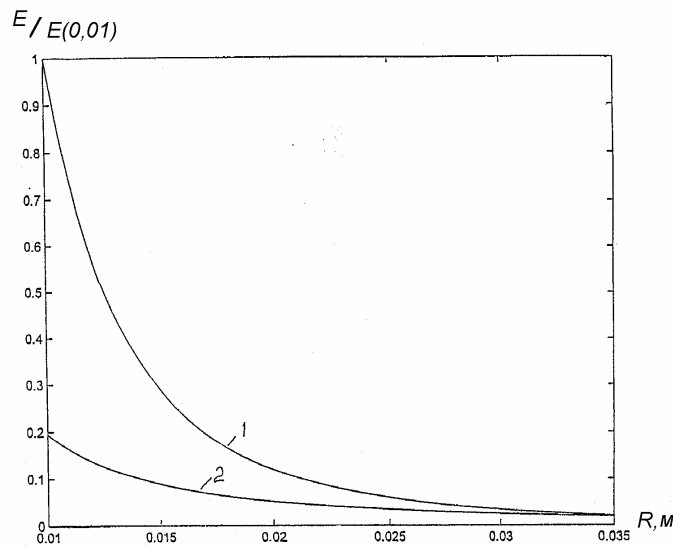


Fig. 2. Electric (1) and magnetic (2) dipole fields.

Such an antenna is described in the papers of Ruoss and Landstorfer [15, 16]. It is the direct slot antenna, with loads on both ends; in other words, it is made of two slots in the form of the letters *T* connected in a foundation. As the authors explain, the application of such a dipole enables the reduction of the irradiation power in a human head from 30 % up to 5.7 % of the total power, which is approximately by 6 times.

Such a slot antenna has an essential disadvantage: it has no circular pattern in a horizontal plane, since, firstly, the antenna has a direct axis and thus the pattern is eight-shaped. Secondly, the slot is carried out as one-sided slot, i.e. it is closed on the head side by cellular telephone metal housing.

### 3. The proposed method

Another method to reduce the unfavorable irradiation is to equip a telephone unit with an auxiliary radiator of low power and to drive it approximately in anti-phase with the main radiator. The action principle of the antenna bases on field interference of two radiators spaced at a distance (Fig. 3). In addition to the main radiating monopole 1, the antenna contains another (auxiliary) monopole 2 of a smaller length (with lower dipole moment), which is situated in the plane, spanning the head centre and the main monopole. Its position is between the head and the main monopole, and it is excited approximately in antiphase with the latter (“approximately” is attributable to the field phase incursion across the interval between monopoles).

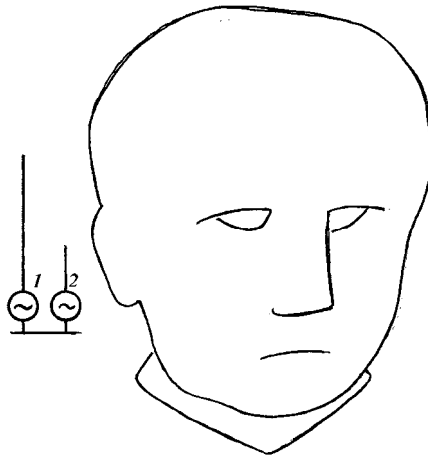


Fig. 3. Two-radiator antenna – placement of main (1) and auxiliary (2) radiators near user’s head.

A skeleton diagram of a telephone unit with an auxiliary radiator is shown in Fig. 4a. The auxiliary radiator is placed between the user’s head and the main radiator, a small distance from the last one, alongside of the head. It allows compensation of both radiators field in a specific (compensation) point inside the head and creating around it an area with a weak field.

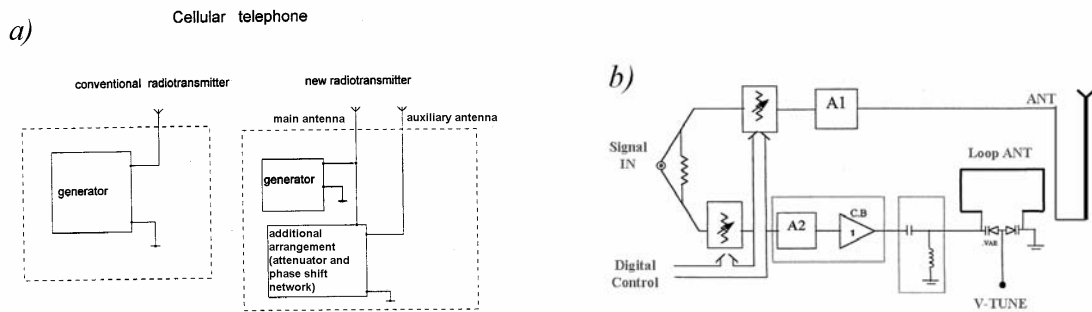


Fig. 4. The telephone unit with the auxiliary radiator of low power: the skeleton diagram (a) and the amplifier circuit (b).

If the both radiators are placed rationally and the amplitude and phase of the auxiliary radiator electromotive force are selected correctly, an overall field that is transmitted will weaken in a predetermined part of a head and practically will not vary in a far region in comparison with the main radiator field. It enables substantial reduction of the power that is absorbed in the predetermined part of head provided that the far region field does not change. At the same time, total irradiation of a human head is substantially reduced.

The proposed method produces a minimum field at a selected point in space rather than at a given far field angle, i.e. it does not distort an antenna pattern. Besides a phone antenna designed to decrease a head irradiation also improves overall performance by recovering a power that would otherwise be absorbed in the head.

During reception an electronic changeover switch hooks up a receiver to the main antenna only.

The similar method is offered in paper [17]. There it is shown by the concrete example that a two-element phased array phone antenna can be designed to greatly reduce the radio frequency irradiation of the user. Unfortunately the consideration method, described in it, is not obvious (not easy-to-interpret) and does not allow to generalize obtained results. Besides the authors of paper [17] choose the field null to lie on the head surface, and the auxiliary radiator is placed remotely from the user's head.

In the article [18] the variant of a placement near to the user's head of two dipoles, one of which is passive, is considered. The application of an only passive radiator as auxiliary one limits an action possibilities to change a structure of a near zone field.

Since distances between both antennas and the compensation point are small, calculation of the antenna fields in a near zone should be realized taking into consideration the radiator's finite sizes. The direct measurement of a field (for example, by using a dummy) represents a difficult task, so there is a need for exact solutions and accurate calculations.

The equations for electromagnetic fields of electrical and magnetic dipoles of finite length are obtained in the paper [19], and the results of these antennas field calculation are also presented there. The electromagnetic field components of an electrical dipole with finite length are

$$\begin{aligned}
 E_R &= 60h_e J_A \left[ \left( 1 - \frac{3L^2}{2R^2} \right) \left( 1 + \frac{1}{jkR} \right) - j \frac{kL^2}{R} \right] \frac{e^{-jkR}}{R^2} \cos \vartheta, \\
 E_\vartheta &= j30kh_e J_A \left[ 1 - \frac{L^2}{4R^2 \sin^2 \vartheta} + \left( 1 - \frac{3L^2}{4R^2 \sin^2 \vartheta} \right) \left( \frac{1}{jkR} - \frac{1}{k^2 R^2} \right) \right] \frac{e^{-jkR}}{R} \sin \vartheta, \\
 H_\varphi &= j \frac{kh_e J_A}{4\pi} \left( 1 - \frac{L^2}{4R^2 \sin^2 \vartheta} \right) \left( 1 + \frac{1}{jkR} \right) \frac{e^{-jkR}}{R} \sin \vartheta, \\
 E_\varphi &= H_R = H_\vartheta = 0,
 \end{aligned} \tag{4}$$

Here a system of spherical coordinates  $(R, \vartheta, \varphi)$  is used,  $h_e$  is an antenna effective length [20],

$J_A$  - a current in antenna base,  $L$  - a dipole arm length,  $k = \frac{2\pi}{\lambda}$  - a propagation constant of a wave in an air,  $\lambda$  - a wavelength. The dipole is located in a coordinate origin along the  $z$ -axis. It was taken into account that quantities  $z$  and  $L$  are small in comparison with  $R \sin \vartheta$ .

Eq. (4) generalizes the known formulas for field component of an elementary electric dipole (Hertz dipole) to the case of a dipole with finite length. The length of Hertz dipole is much less than the wavelength and the distance to the observation point, while the current amplitude and phase along the dipole are the same along its length. The symmetric dipole arm length is comparable to the wavelength, and the current along it follows sine distribution law. Eq. (4), as well as known formulas for fields of Hertz dipole, take into account the terms, inversely proportional to the first, second and third degrees of distance  $R$  to the observation point, i.e. are valid both in the far-field and in near zones.

Similarly for a horizontal circular loop of a finite radius  $a$

$$E_{\varphi} = 30k^2 J_s \frac{e^{-jkR_0}}{R_0} \left[ 1 + \alpha + \frac{k^2 a^2}{2} \alpha (1 + 3\alpha + 3\alpha^2) - \frac{3}{8} k^2 a^2 \left( \frac{1}{3} + 2\alpha + 5\alpha^2 + 5\alpha^3 \right) \sin^2 \vartheta \right] \sin \vartheta, \quad (5)$$

$$E_R = 0.$$

Here  $s = \pi a^2$ ,  $\alpha = \frac{1}{jkR_0}$ , where  $R_0$  is a distance from a loop center to an integration point. The loop by a radius  $a$  lies in a plane  $xOy$ , and the center coincides with a coordinate's origin. It is taken into account that the loop radius is small ( $a \ll \lambda, R_0$ ), and that the amplitude and phase of current  $J$  along a loop wire does not vary.

#### 4. Numerical and experimental results

In Fig. 5a the calculations results of two monopole antennas depending on distance from the main radiator are presented. Dimensions in the Figure are given in meters. The distance between antennas is 0.02 m. The auxiliary radiator is placed along the head tangent, i.e. the area occupied by the head is from the right of point  $R=0.02$  m. The main antenna field strength (curve  $E_1$ ), the auxiliary antenna field strength (curve  $E_2$ ), the overall field strength (curve  $E_1 + E_2$ ) are all displayed in the Figure. The calculations are performed at a frequency 900 MHz. The fields' magnitudes are normalized to the main antenna field magnitude  $E_1(0.01)$  at a distance of 0.01 m from its axis.

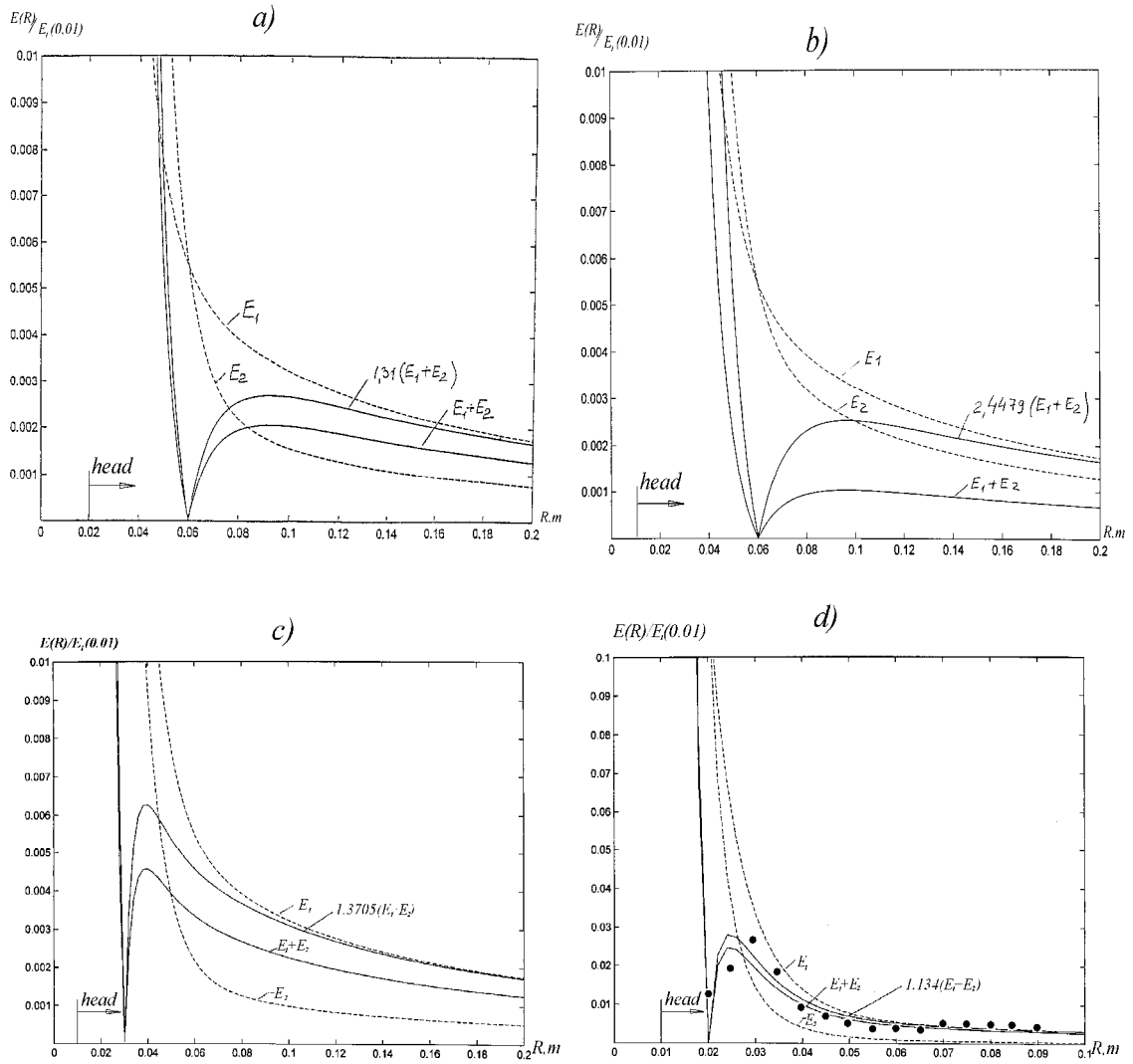


Fig. 5. The field strength of radiators depending on distance between monopole antennas:

$$a - R_1 = 0, R_2 = 0.02, R_c = 0.06, E_2 = 0.397E_1e^{j3.53},$$

$$b - R_1 = 0, R_2 = 0.01, R_c = 0.06, E_2 = 0.7101E_1e^{j3.3116},$$

$$c - R_1 = 0, R_2 = 0.01, R_c = 0.03, E_2 = 0.2797E_1e^{j3.2309},$$

$$d - R_1 = 0, R_2 = 0.01, R_c = 0.02, E_2 = 0.1192E_1e^{j3.1725}.$$

The compensation distance (the distance between the compensation point and the main radiator) is  $R_c = 0.06m$ . In order to ensure the antenna field's mutual compensation at this distance, it is necessary that the dipole moment  $E_{02}$  of the auxiliary radiator be equal to

$E_{02} = 0.397E_{01}e^{j3.53}$ , where  $E_{01}$  is the dipole moment of the main radiator. From the Figure one can see that for a distance of up to 0.2 m (the area of user's head) the overall field is reduced. At a large distance from the radiators, the field magnitude is smaller by a factor 1.31 in comparison with the original one. If both antennas fields are increased by 1.31 times, then the overall field strength at a large distance will be the same as original one. However one must increase the overall feeding power approximately twice.

The calculation results for two monopole antennas located at a distance of 1 cm from each other are presented in Fig. 5b. Here the overall field is reduced by a greater amount. However, at a reduction of the distance to the compensation point, the difference between a main antenna field and the total field of two antennas in far zone decreases (see Fig. 5c, where  $R_c = 0.03m$ , and Fig. 5d, where  $R_c = 0.02m$ ).

In the case corresponding to Fig. 5d the overall feeding power should be increased approximately by 20%, i.e. the battery life reduces slightly. This increase is smaller, if the compensation distant will be smaller.

When two antennas, such as monopoles, are put close to each, their performance will be significantly affected. The total radiation field is not the simple addition of the fields radiated by two individual antennas. But account must be taken that, when the mutual compensation of basic and auxiliary antennas fields is made, a relation of their dipole moments rather than antennas mutual coupling serves as a main criterion. A current distribution along them is automatically taken into account by means of radiators effective lengths.

A loop placed on phone housing can be used as an auxiliary antenna too. At that the loop should be placed at a side surface of a phone unit in order to fields polarizations of main and auxiliary antennas coincide.

The calculation results for monopole and loop antennas are presented in Fig. 6a. The main antenna (monopole) is located in coordinate's origin, the center of auxiliary antenna (loop with radius  $a = 0.3 m$ ) lies at a distance  $R_2 = 0.015 m$  from it. The compensation distance is  $R_c = 0.06m$ . In Fig. 6b the similar curves are given for  $R_2 = 0.01m$ ,  $R_c = 0.03m$ ,  $a = 0.05m$ .

However, great loops dimensions render these antennas bulky and unusable.

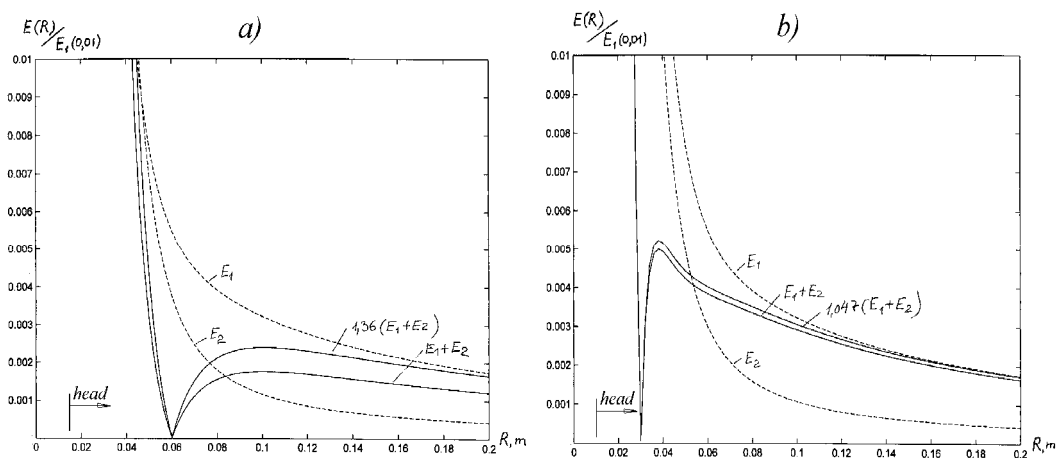


Fig. 6. The field strength of radiators depending on distance between monopole and loop

antennas: a -  $R_1 = 0$ ,  $R_2 = 0.015$ ,  $R_c = 0.06$ ,  $E_2 = 1.4551E_1e^{j3.92}$ ,

b -  $R_1 = 0$ ,  $R_2 = 0.01$ ,  $R_c = 0.03$ ,  $E_2 = 0.881E_1e^{j3.2727}$ .

The calculations show that the fields of two antennas in a head direction and in the opposite direction at a distance greater than 0.2 m are almost the same fields, in other words the pattern is omnidirectional. An effect of the second antenna on the pattern of the first one is negligible, since the second antenna is an obstacle in the form of an isolated conductor of a small radius. For the same reason, the second antenna produces a small effect on a transmitter output stage tuning (tuning can be performed by a slight change of the length of an antenna).

On the other hand, one can see from the Figures that the power dissipated in the user's head is reduced substantially, since it represents a function of the square of the area under the field curve.

Fig. 4b displays the circuit of the amplifier used for experimental check of the calculated results. The dependence of a total field on distance  $R$  and essential field attenuation in the given area (in the compensation zone), which was obtained by calculations, has been also verified experimentally by means of instruments for measurement of field in near zone. The results of experimental check of the total field are presented in Fig. 5d (by closed circles). An experimental procedure was analogous with the procedure, which is described in the article [21]. Experiment has shown agreement with calculation.

## 5. Decrease of irradiation

Let  $K$  be an irradiation decrease factor (a magnitude of a human head irradiation power decrease) caused by placing of the auxiliary radiator. The calculations are carried out under the formula

$$K = \frac{P_c}{P_1}. \quad (6)$$

Here  $P_c$  and  $P_1$  represent the irradiation powers in the cases of using both antennas and only basic radiator (antenna 1), respectively, if the fields in either case in a far zone in a maximum radiation direction are identical:

$$P_c = \int_{(v)} |E_1 + E_2|^2 \sigma dv, \quad P_1 = \int_{(v)} |E_1|^2 \sigma dv, \quad (7)$$

where  $\sigma$  is the head tissues conductivity,  $V$  is the head volume.

In the first approximation the sphere with  $R_{hh}$  as radius is a model of the head form, and the antenna is drawn parallel to this sphere tangent on a distance  $h$  from it (see Fig. 7a). It is possible to show (see Appendix) that in calculation of integrals  $P_c$  and  $P_1$  the sphere can be replaced by a hemisphere (see Fig. 7b), and its interior and exterior radiuses are equal accordingly to  $R_1 = h$  and  $R_2 \approx 1.15R_{hh}$ . Omit the factor  $\sin \vartheta$  in expression for a field. Then, considering  $\sigma$  as a constant, we find:

$$P_1 = \sigma \int_{R_1}^{R_2} |E_1(R)|^2 R^2 dR, \quad P_c = \frac{\sigma E_1^2(\infty)}{|E_1(\infty) + E_2(\infty)|^2} \int_{R_1}^{R_2} |E_1(R) + E_2(R)|^2 R^2 dR. \quad (8)$$

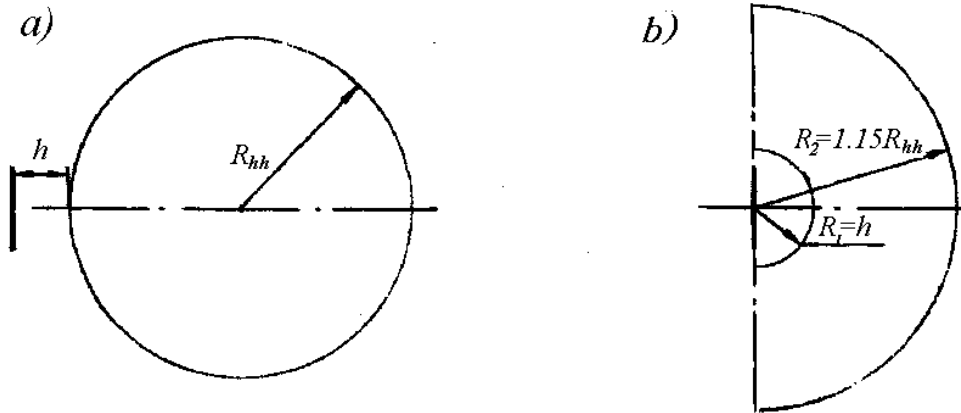


Fig. 7. The change of the sphere to the hemisphere: a - the dipole near the sphere, b - the dipole near the hemisphere.

The calculations of fields in a near zone are performed in the work by the formulas (4) in view of dielectric permittivity of tissue, and the calculations of the irradiation powers are

performed by the formulas (8). The accuracy of this method is similar in this case to the accuracy of simulation software (such as FDTD package). The calculations results are verified by measurement of the total near field dependence on distance  $R$ , including the field in the compensation zone (see section 4, last paragraph).

In Fig. 8 the combined chart for the irradiation decrease factor is given for two monopoles. Along the axis of abscissas, the distance to a compensation point is postponed. The different curves correspond to various distances  $h$  from a main antenna center to a human head (an auxiliary radiator is placed along the head tangent). It is visible, that each curve has a minimum, which is the optimal compensation point, and the value of magnitude  $K$  in this point varies in limits 0.27-0.35. Hence the calculations show that at an auxiliary antenna arrangement in a gap between a head and a basic antenna, by the right choice of an auxiliary antenna signal amplitude and phase, it is possible to reduce an irradiation to approximately three-four times its present size. For this purpose, the compensation point should be selected near a surface of a human head. At that the overall feeding power increases slightly (about 20%).

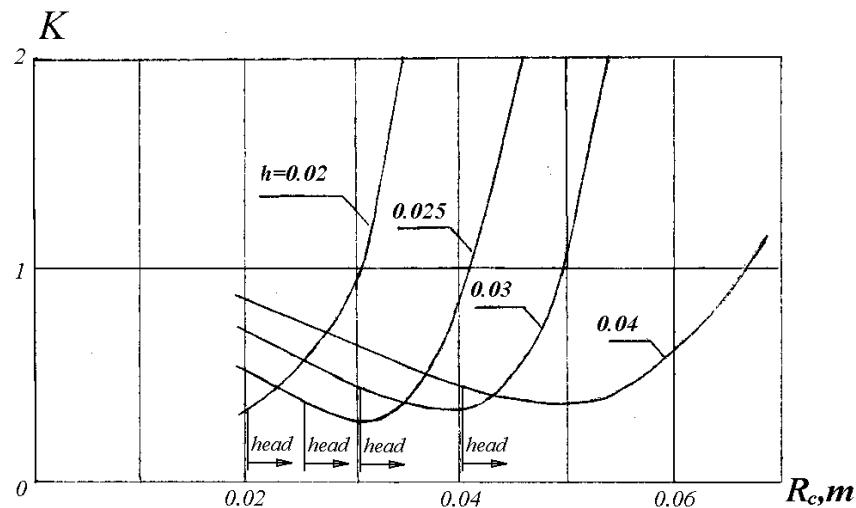


Fig. 8. The irradiation decrease factor at application of two monopoles.

When examining results, it is necessary to keep in mind, that field attenuation on an additional radiator application takes place not only on distance  $R_c$  from the basic antenna, but also in a zone about 1 cm deep. It follows from Fig. 8, that in practice it is best to use variants with  $h=2.5$  cm,  $R_c=3$  cm. In this case the main and the auxiliary radiators (height about 8.3 cm and 3.0 cm, respectively) are installed on the top of a metal housing of a cellular telephone on a distance 2.5 cm from each other (Fig. 10). The precise sizes of radiators are established experimentally for the used generator and the given phone housing. It is possible to use variant

with  $h=3$  cm,  $R_c=4$  cm, and also intermediate ones. The variant with  $h=4$  cm and  $R_c=5$  cm is the less practical one. This is true and for variant with  $h=2$  cm. However, and in the last case, an additional radiator application ensuring the fields compensation at  $R_c=2-2,5$  cm enables a significant reduction in thermal losses in a head surface layer about 0.5 cm deep, which results in a decrease of dissipation power almost by a factor of three.

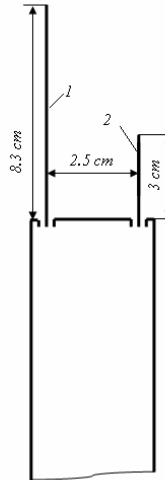


Fig. 10. The installation of the main (1) and the auxiliary (2) radiators (height about 8.3 cm and 3.0 cm, respectively) on the metal housing of a cellular telephone.

This method also permits the cancellation of an unfavorable field in the region most sensitive to irradiation, even in the case of minor irradiation.

## 6. Conclusion

The proposed method and the theoretical analysis with simulations show that there exists a way to solve irradiation problem of human tissues. The described method enables reduction of irradiation by a factor of three to four. At the same time, a quality of communication with the correspondents (base stations) in any direction is preserved.

This near-field cancellation technique can be used in a variety of cases, for example for decreasing two closely located antennas mutual effect (interference).

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#### **Appendix. Integration over sphere by pass to integration over hemisphere.**

An antenna represents a dipole located in a coordinate's origin along the  $z$ -axis. A dipole field is  $E(R, \vartheta, \varphi) = E(R)\sin \vartheta$ .

Let us calculate a quantity of energy dissipated inside a sphere of radius  $R_0$ , with the center on the  $x$ -axis, with the surface passing through a coordinates origin (see Fig. 9a). It is easy to prove that the coordinate  $R_1$  of any point on a sphere surface is equal

$$R_1 = 2R_0 \sin \vartheta \cos \varphi. \quad (A1)$$

To demonstrate it, one can deduce from the Figure  $R_0^2 = R_1^2 + R_3^2 + R_4^2$ , where

$R_3 = R_1 \sin \vartheta \sin \varphi$ ,  $R_4 = R_1 \sin \vartheta \cos \varphi - R_0$ , whence expression (A1) immediately follows.

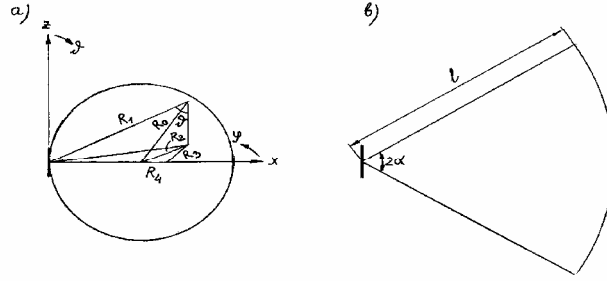


Fig. 9. Integration over sphere and over hemisphere: a – the sphere, b – the circular cone.

A power dissipated inside the sphere is calculated as an integral over a volume  $V$  :

$$P = \int_{(V)} P_0(R, \vartheta, \varphi) R^2 \sin \vartheta dV, \quad (A2)$$

where  $P_0(R, \vartheta, \varphi) = E^2(R, \vartheta, \varphi)G$  is the power dissipated in a volume unit,

$E(R, \vartheta, \varphi) = E(R)\sin \vartheta$  is the electrical field strength in a point  $(R, \vartheta, \varphi)$ ,  $G$  - specific medium conductivity inside a sphere. From (A2) and (A1) we receive

$$P = 4G \int_0^{\frac{\pi}{2}} d\varphi \int_0^{\frac{\pi}{2}} \sin^3 \vartheta d\vartheta \int_0^{2R_0 \sin \vartheta \cos \varphi} E^2(R) R^2 dR.$$

If in the first approximation

$$E(R) = \frac{E_0}{R}, \quad (A3)$$

where  $E_0 = \text{const}(R)$ , then

$$P = \frac{3\pi}{2} E_0^2 G R_0. \quad (A4)$$

Let us replace a sphere by a circular cone with an angle  $2\alpha$  at a top (Fig. 9b). The power dissipated inside a cone with generator length  $l$  is equal  $P_\alpha = 4 \int_0^\alpha d\varphi \int_0^\alpha \sin \vartheta d\vartheta \int_0^l P_0(R, \vartheta, \varphi) R^2 dR$ .

If (A3) is true,  $P_\alpha = 4\alpha \left( \frac{2}{3} - \cos \alpha + \frac{1}{3} \cos^3 \alpha \right) E_0^2 G l$ , that is at  $\alpha = \frac{\pi}{2}$

$$P_\alpha = \frac{4\pi}{3} E_0^2 G l. \quad (A5)$$

As it is visible from (A4) and (A5), the magnitudes  $P$  and  $P_\alpha$  are identical, if  $l = \frac{9}{8}R_0$ . Thus in the first approximation, the integration over a sphere volume can be replaced by an integration over a cone volume with generator length  $\frac{9}{8}R_0$ .

Michael Bank



Michael Bank received the B.A and M.Sc. degrees in communicational engineering from the Leningrad Institute of Communications in 1960, received the Ph.D. degree in 1969 in the field of FM signal detection. He received Doctor of Science degree (Russian equivalent of professor) in 1990. Since 1992 he is a consultant of Israel communicational company Bezeq and a lecturer in the Holon Academic Institute of Technology. His research interests include digital modulation, digital signal processing and RF receiving theory.

Levin Boris



Levin Boris was born in Saratov, Russia, in January 1937. He graduated from Leningrad Polytechnic Institute in 1960, received his Ph.D. in radio physics in 1969 and Doctor of Sciences Degree in Physics and Mathematics from S.-Petersburg Polytechnic University in 1993. From 1963 to 1998 he worked for the Design Office “Svyazmorproyekt” of Russia Shipbuilding Department. From 2000 to 2002 he worked for the Company “MARS”, Holon, Israel.

Levin Boris has authored 3 books, 70 original papers in technical journals and 26 papers in proceedings of international scientific conferences. His main research interests are in the fields of the electromagnetic theory, the theory of linear antennas and antenna optimization.