Low SAR Phased Antenna Array for Mobile Handsets

(*Invited Paper*)

J. Moustafa, N. J. McEwan, R. A. Abd-Alhameed and P. S. Excell
j.moustafa@bradford.ac.uk, nmcewan@Filtronic.com, r.a.a.abd@bradford.ac.uk, p.s.excell@bradford.ac.uk
Mobile and satellite Communications Research Centre, Bradford University, Bradford, BD7 1DP, UK

Abstract**—**A two-element phased antenna array for a mobile handset is investigated using the Finite Difference Time Domain (FDTD) method. The array is designed to provide a spatial minimum in SAR in the near field zone inside the human head. The optimisation algorithms to obtain the minimum peak specific absorption rate (SAR) and minimum total absorbed power are addressed. It is found that these criteria are not seriously conflicting. The effects of the head-array spacing on the optimum array feeding voltages and the reduction in SAR are discussed. The results are compared with those from a normal single element handset, showing that the overall efficiency and azimuth coverage are improved and that peak specific absorption rate in the head can be reduced by at least 8 dB.

Key words**—**Phased antenna array, Finite Difference Time Domain (FDTD), Specific Absorption Rate (SAR).

I. INTRODUCTION

It has been shown experimentally and theoretically [1-3] that a handset antenna can be designed to direct the radiated power away from the head. Obviously, the simple approach would be to design a simple two-monopole element array for a cardioid pattern with a far-field null in the direction of the head [4, 5].

This paper extends the work in [4, 5] by using the Finite Difference Time Domain (FDTD) method, and by treating a wide range of head-antenna spacings. The FDTD method confers some advantages over the previously used integral-equation representation [4, 5] in allowing more investigations of the effect of the array when the head juxtaposed with the handset. It also gives information on the effect of the head on the steering voltages required for feeding. The array considered is for a personal communications handset working at frequencies near 2 GHz. It is designed to provide a spatial null in the near field zone within the human head, which is treated as a lossy dielectric sphere for initial studies.

It will be seen that the overall efficiency and azimuth coverage are improved and the peak specific absorption rate in the head can be reduced by at least 8 dB, as compared with a conventional single monopole element handset.

II. ARRAY CONCEPT

It was found previously that the most promising handset antennas were those with the radiating element shielded in some way from the user's head, and having extension in the direction normal to the head surface [4-6]. The most encouraging result was that the reduction of absorption in the user's head could be accompanied by an improvement in the radiated power level at almost all azimuth angles.

The typical structure needed to achieve this was a reflecting plate or shield interposed between a cylindrical radiator and the head. Other examples, not fundamentally different in principle, are the microstrip patch radiator and PIFA where the ground plane resembles the reflecting plate. Both of these cases could be viewed as a form of array in which the shield or the ground plane constitutes the second element and is parasitically excited.

Thus, it is clear that these structures may not realise all the potential advantage of an array, because the ratio of excitations in the driven element and the parasite is incidental and not under the complete control of the designer. However, the reflector plate is a structure with extension in two dimensions. This has too many degrees of freedom, and it is not clear how the currents in such an extended structure could be controlled by the designer [7]. To make the problem easier to analyse, the second element in the array needs to be simplified to one whose excitation is described by just one parameter and is controllable by choosing the voltage or current at a single port or terminal pair.

It was shown by McEwan et al [7-9], that the most sensitive regions of the head could be selectively protected using the proposed two element array. Space averaged exposure could be reduced at the time as improving the azimuthal coverage. Referring to earliest papers [1, 9-11], the scattering of an EM wave incident on a sphere was solved by expanding the incident, internal and scattered waves as a series of spherical waves.

III. PRACTICAL HANDSETS

The results obtained by [8, 9] using ideal dipoles were encouraging, but the antenna is not very realistic. It is clear that the elements individually need not produce linear polarisations at any point inside the head, nor do their polarisations have to be identical. It would be expected from the geometry that they actually

1054-4887 © 2006 ACES

produce polarisation ellipses with a fairly high axial ratio and the longest axis roughly parallel to the dipoles.

In a practical handset, the two elements of the phased array would work in the presence of the set's ground plane. This means that, when each element is excited in turn, the currents produced are physically separate on the monopole elements, but to a large extent spatially coincident (though not of identical configuration) on the common ground plane against which they are both excited. Furthermore, there must be currents flowing transversely to the board plane, because the elements are separated along the normal to that plane. A realistic practical model is a complete metallic box with two monopoles mounted on its top.

IV. SOFTWARE STRUCTURES

Earlier work [4] using only the MoM encountered difficulties in the memory requirements. The results obtained were fairly good but could only exploit an extremely coarse representation of the head. The hybrid technique of MoM and FDTD [5] is excellent when there is no physical contact between the handset and the head. The present work uses only the FDTD method [12]: this is suitable for this particular situation where the handset is in direct contact with the head. The antenna geometry proposed here (see Figure 1) makes the method applicable since only straight monopoles are to be modelled. The method is augmented by the thin wire code that takes account of the monopole wire radius and enables prediction of the admittance matrix of the antenna for optimisation purposes. The method will find currents and fields throughout a structure when it is excited by specified voltage sources at arbitrary points. An additional piece of software was written to optimise the excitation of the array. This has two very important features: (a) It does not require repeated field solving to optimise the excitation of the array. (b) It solves rigorously the problem of optimising the array to minimise either the total power absorbed in the head or the worst point value of SAR occurring in the head.

V. LINEARLY POLARISED PHASED ARRAY ANTENNA

The near field (E_{total}) produced from linearly polarised phased array at any chosen point in the desired region should be made to be equal or very close to zero. This is obtained by a proper choice of the complex feed voltage source ratio R_v of the second array element relative to the first. The problem obviously requires that the phases of field components are included in the field solution, while normal SAR calculations only require the magnitude of the electric field. Since the problem is linear, a free space null can be obtained by summation thus:

$$E_{total} = E_1 + R_v E_2 = 0 \tag{1}$$

where E_1 and E_2 are the induced near fields at the worst case SAR location for each element when they are excited separately with unit voltages of the same phase. If E_1 and E_2 are proportional to each other, i.e. the two elements are producing the same polarisation at the point in question, then the R_v magnitude and phase required to satisfy equation (1) are given as follows:

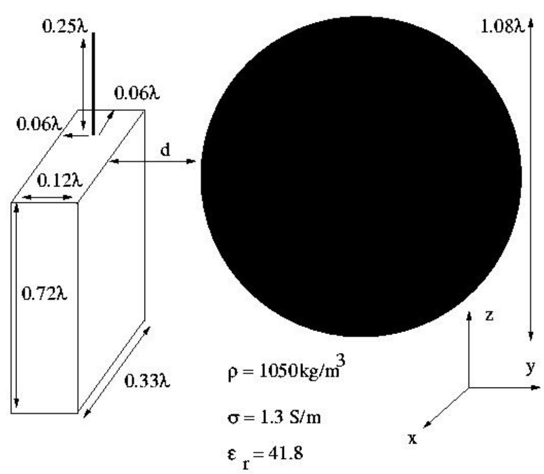
$$|R_v| = |E_1/E_2| \tag{2}$$

$$\theta = \phi_{E_1} - \phi_{E_2} + 180^\circ \tag{3}$$

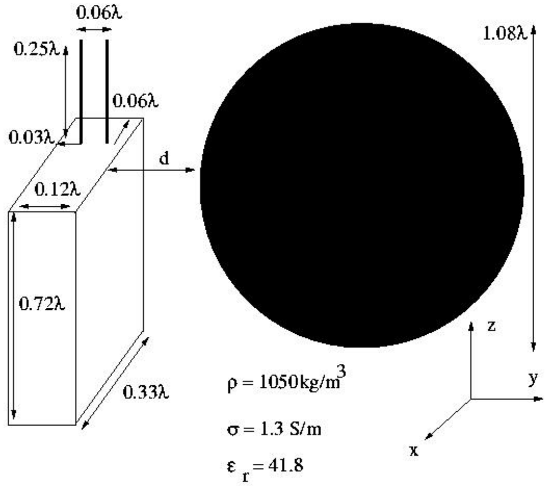
where θ, φ_{E1}, φ_{E2} are the phases of R_v, E_1 and E_2 respectively, and need to be calculated accurately to place the appropriate null at the point in the head that would otherwise be a hot spot.

These expressions for the required voltage ratio R_v between the two array elements are only appropriate for cases where the two elements produce the same polarisation, at the spatial point where nulling is to be performed. In practice, the only case where this obviously the holds is where the polarisations are approximately linear and in the same direction.

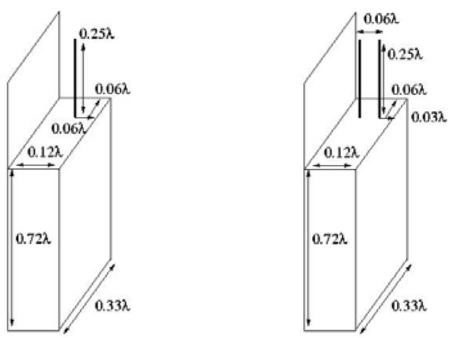
The case of non-identical and noticeably elliptical polarisations applies for any realistic two-element phased array on the top of a handset. In this case much more elaborate optimisation procedures are required to obtain an accurate value of R_v for minimising the power absorbed or the maximum SAR inside the user's head. These procedures that were developed to optimise the more complex phased antenna arrays are now described. Throughout the remaining discussion, we use the notation SAR_{max} to denote the peak SAR (with or without a stated volume averaging) in the head, regardless of where it occurs. The total power absorbed in the head will be denoted P_{abs}.



(a)



(b)



(c) (d)

Fig. 1. (Top two) the basic structure of the mobile handset next to a spherical head with the following antenna configurations; (a) single monopole; (b) two-element array. (Bottom) wire grid models for different innovative geometries: (c) single monopole with reflector sheet; (d) two element array with reflector.

VI. SAR OPTIMISATION PROCEDURE

The complex excitation voltages of the array can be optimised to minimise at least three different quantities:

(1) The SAR at a selected fixed point in the head;
(2) P_{abs};
(3) SAR_{max}, i.e. its peak local value anywhere in the head.

The first kind of optimisation would be appropriate if it is believed that some particular small anatomical structure in the head is the most sensitive to a thermal or athermal hazard. In the present state of biological knowledge there is probably little basis for choosing any such structure, except possibly the central structures in the brain at which SAR is already greatly reduced by intervening tissue. Optimisation (3) would be appropriate if there is an athermal or thermal hazard for all tissues and it rises rapidly above some threshold value of SAR. An optimisation of type (2) could be useful if there is a probabilistic risk of, for example, abnormal cells being produced throughout the entire brain, and this probability is a nearly linear function of local SAR. It is beyond the scope of the present work to throw any light on these biological aspects. Instead, results will be presented for optimisations of both types (2) and (3), which are probably the most useful.

All the optimisations assume that a numerical solution of the fields inside the head are available at the outset. The type (1) optimisation can be easily performed analytically as follows. Let E_1, E_2 be evaluated at a fixed cell in the head where the SAR is to be minimised. Since the electromagnetic responses are linear, the fields induced in the head due to the feeding of both antennas can be expressed using the voltage ratio as $V_1(E_1+R_vE_2)$ where V_1 is the excitation voltage of element 1. The problem of minimising SAR with respect to R_v is equivalent to minimising $|E_{total}|^2$ where E_{total} is the resultant electric field produced from the array. $|E_{total}|^2$ can be written as $|V_1|^2 f$ where f depends only on R_v Hence:

$$f = (E_1 + R_v E_2) \bullet (E_1 + R_v E_2)^* \tag{4}$$

$$f = |E_1|^2 + |R_v|^2 |E_2|^2 + R_v^* E_1 \bullet E_2^* + R_v E_1^* \bullet E_2. \tag{5}$$

Let $R_v = me^{j\theta}$ and $E_1 \bullet E_2^* = ke^{j\phi}$ then:

$$f(m,\theta) = |E_1|^2 + m^2 |E_2|^2 + 2km\cos(\phi - \theta) \tag{6}$$

where '•' represents vector dot product. Changing R_v for a fixed value of $|V_1|$ causes a change in the total power transmitted from the array. In practical operation with appropriate impedance matching, the value of $|V_1|$ would make the total power transmitted by the array equal to its design value. Hence R_v should be optimised on the assumption that constant total power P_{rad} emerges from the array feed terminals, although some of this is subsequently absorbed in the user. It is shown below that P_{rad} can be expressed in the form:

$$P_{rad} = |V_1|\, g(m,\theta) \tag{7}$$

where the function g also depends on the admittance matrix of the array, as modified by the interaction with the user. It is now clear that the optimisation problem is that of minimising f while keeping g constant, or equivalently of minimising the ratio f/g. The required R_v can thus be found analytically as the solution of the simultaneous conditions:

$$\frac{\partial}{\partial m}\left[\frac{f(m,\theta)}{g(m,\theta)}\right] = 0, \qquad \frac{\partial}{\partial \theta}\left[\frac{f(m,\theta)}{g(m,\theta)}\right] = 0. \tag{8}$$

An optimisation of type (2) can be performed by a similar method, if the differentiation is performed on the sum of SAR over all cells. The type (3) optimisation cannot be performed easily by differentiation because the cell location at which SAR_{max} occurs may change as the value of R_v is varied.

A numerical algorithm has therefore been developed which performs the type (3) optimisation without making any assumptions about the initial location of the worst cell or how its position might change with changes in R_v. It is easy to also include in this algorithm the type (2) optimisation by a "brute force" rather than a differentiation method.

The final SAR optimisation algorithm for any two-element phased antenna array is illustrated in Fig. 2 and can be explained as follows:

1. The FDTD computation was initially run twice, with each element in turn excited with a terminal voltage of 1V rms and zero phase, while the other element was short circuited. For each case, the complex electric field vector at the centre of each cubical cell of the head model was stored in an array. (i.e 3N complex field values, where N is the number of cubic cells in the head model used).
2. From each FDTD run the current at the base of each element is computed, so that the [Y] (admittance) matrix of the two antenna ports, as modified by the head proximity effect, is then known.
3. The assessment of the reduction in RF absorption was made on the assumption that P_t (the total power leaving the handset) remained constant with a value of 1 Watt, with the head present, and as the excitation is varied. The variable design parameter was again taken as the complex ratio of the element excitation voltages $R_v = V_2/V_1$. The total power P_t leaving the handset using RMS values of voltages is given by:

$$P_t = \mathrm{Re}\ (V_1 I_1{}^* + V_2 I_2{}^*). \qquad (9)$$

Since $\mathrm{Re}(XY^*) = \mathrm{Re}(X^*Y)$, then P_t can be written as:

$$P_t = \mathrm{Re}\left[\begin{bmatrix} V_1^* & V_2^* \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}\right]. \qquad (10)$$

Arbitrarily taking $|V_1|$ as unity, this leads to:

$$P_t = \mathrm{Re}[Y_{11} + Y_{12} R_V + Y_{21} R_v^* + Y_{22} |R_V|^2] \qquad (11)$$

where Y_{ij} (i=1,2, j=1,2) are the admittance matrix elements of the two-port antenna.
4. Once a value of R_v has been set, which is done in the outer loop of the program, then the electric field inside each cell in the head can be found as ($E_1 + R_v E_2$), and the inner loop of the program is used to compute both the maximum SAR and the summation of SAR over all cells. Results are divided by P_t, calculated from (11) to impose the condition that the total power leaving the handset is 1 watt.

Figure 2 shows the form of the program that was used for minimisation of $P_{abs.}$ The innermost loop is performing a summation of SAR over all cells. In the alternative form for optimising SAR$_{max}$, the inner loop simply updates the highest value of SAR that has yet been found. The outer loop locates the optimum value of R_v in both cases. It also outputs a data file defining P_{abs} or SAR$_{max}$ as a function of R_v, which is used to generate plots for visual inspection.

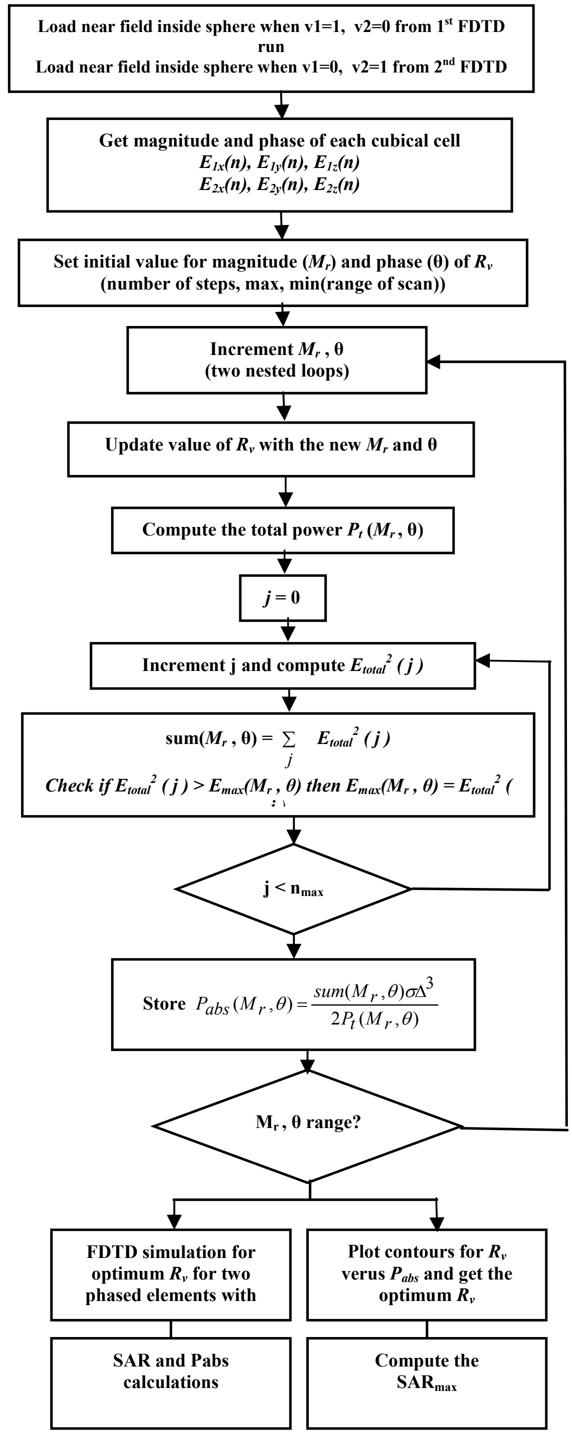


Fig. 2. Flow chart of implementation of SAR optimisation algorithm.

VII. HANDSET AND HEAD MODELS

The handset and head models used are shown in Fig. 1. The quarter wavelength monopoles were chosen to be of radius 0.0045λ, where λ is the free-space wavelength at 1.8 GHz. For defining R_v, element number 1 is taken as the one further from the head. The box size adopted was 0.12λ × 0.333λ × 0.72λ and the head was approximated by small cubes, each with a side of 0.015λ, forming a discretised approximation to a sphere. The sphere was assigned homogeneous dielectric properties representing the average values for the human head: a relative permittivity and conductivity of 41.8 S/m and 1.3 S/m respectively, for a working frequency of 1.8 GHz. The cell size was chosen to be 2.5 mm. Although the FDTD method can handle an inhomogeneous head of more realistic shape, the simple model was considered sufficiently accurate for evaluating the array performance [13,14]. The problem space size of the FDTD method was 85 × 101 × 107 cells with an additional 6-cell layer for the Perfectly Matched Layer (PML). Several configurations of monopoles attached to, and driven against, this box were modelled, including conventional single monopoles for comparison. The effect of including a reflecting plate with a single monopole and the two-element array was also investigated; these geometries are as shown in Fig. 1(c, d).

As the array spacing is only 0.06λ, it has to operate with very strong mutual coupling between its elements. The computed Y matrix at 1.8 GHz, with the head model present, is $Y_{11} = 0.0053 - j0.020$, $Y_{22} = 0.0125 - j0.024$, $Y_{21} = -0.00056 + j0.024$. The mutual effects are automatically included in the above optimisation procedure for R_v. They are critical in the design of the practical power splitter which must also include impedance matching, but they prove quite straightforward to allow for.

VIII. ANALYSIS OF THE NUMERICAL RESULTS

The single monopole antenna, single monopole antenna with reflector, two-element array, and two element array with reflector, have been investigated and the results compared with some available data [5,7,9]. Tables 1 and 2 present the performance of the above antennas. Table 1 shows the maximum unaveraged SAR in any FDTD cell, when the excitation ratio R_v is optimised for minimum SAR_{max} in column (c), or optimised for minimum $P_{abs,tot.}$ in column (d). Since the electromagnetic problem is linear, any absorbed power can be expressed as a fraction of the transmitted power and hence for example an SAR can be expressed in kg^{-1}. The figure given is thus the actual W/kg when the transmitted power is 1 Watt. This avoids the confusion caused by authors basing published SAR figures on different assumed values of transmitted power.

It is found from Table 1 that the reductions in the maximum SAR for the monopole with reflector, two element array, and two element array with reflector, as compared with a single λ/4 monopole, are -8.2 dB, -10.3 dB, and -15.4 dB, respectively when the head is juxtaposed with the handset (0 cm distance). As the separation distance between the head and the handset is increased to 2 cm, the reductions become -4.4 dB, -7.7 dB, and -7.8 dB, respectively. These values have been compared with some other published figures found for similar structures using MoM [4,7,9] and hybrid method [5], and for 2 cm distance only. Using MoM, the predicted reduction for the two element array and the two element array with reflector, with respect to a single monopole element, are –6.3 dB and –7.9 dB, while the predicted reduction using the hybrid method for the two element array is –8.3 dB. It is seen that the results of FDTD are close to those from other methods. Note that in Tables 1 and 2, the excitation ratio is re-optimised when the antenna-head separation is changed.

Table 1. The maximum SAR for the monopole with reflector, two element array, and two element array with reflector, as compared with a single λ/4 monopole.

D (cm)	Unaveraged SARmax (kg^{-1})				
	a	b	c	d	e
0.0 cm	68.80	10.38	6.49	7.22	1.99
0.5 cm	23.53	4.37	2.78	2.95	0.99
1.0 cm	11.12	2.82	1.55	1.73	0.97
1.5 cm	6.08	1.89	0.97	1.11	0.79
2.0 cm	3.73	1.37	0.64	0.75	0.62

(a) Monopole, (b) Monopole with reflector, (c) Two element array (optimised to minimise SARmax), (d) Two element array (optimised to minimise total power absorbed), (e) Two element array with reflector (optimised to minimise SARmax).

Table 2. The total power absorbed in the spherical head, normalised to 1W input, obtained by optimising for minimum SAR_{max} and for minimum $P_{abs,tot}$.

D (cm)	Total Power absorbed (milliunits)				
	a	b	c	d	e
0.0 cm	674	304	237.6	216.6	118.5
0.5 cm	446	185.6	153.2	143.6	83.3
1.0 cm	301	148.16	114.4	111.6	79
1.5 cm	241	117.77	87.8	85.8	65.8
2.0 cm	161	94.07	67.95	66.1	54.5

Table 2 shows the total power absorbed in the spherical head, normalised to 1W input, obtained by optimising for minimum SAR_{max} and for minimum P_{abs}. It is immediately apparent from comparing columns c and d in each table that the strategies of optimising SAR_{max} or P_{abs} are not seriously in conflict, as either choice gives a reduction in both quantities that is not far below the optimum. For comparison with some related work [4,5], the total power absorbed in the head, for the case of the two element antenna separated 2 cm from the head, was found here as 6.6% of the radiated power, while for the two element array with reflector it is 5.45%. These figures indicate a low interaction between

Table 3. The maximum SAR for the various cases but averaged over 1g and 10g of head tissue.

	SARmax (Monopole)			SARmax (Monopole with reflector)		
D (cm)	Unaver (kg^{-1})	1gm (kg^{-1})	10 gm (kg^{-1})	Unaver (kg^{-1})	1 gm (kg^{-1})	10 gm (kg^{-1})
0.0cm	68.80	29.11	16.44	10.38	4.59	2.93
0.5cm	23.53	12.70	7.75	4.37	2.50	1.75
1.0cm	11.12	6.42	4.14	2.82	1.74	1.24
1.5cm	6.08	3.67	2.48	1.89	1.21	0.87
2.0cm	3.73	2.35	1.62	1.37	0.85	0.61

	SARmax (Two element array)			SARmax (Two element array with Reflector)		
D (cm)	Unaver (kg^{-1})	1gm (kg^{-1})	10 gm (kg^{-1})	Unaver (kg^{-1})	1 gm (kg^{-1})	10 gm (kg^{-1})
0.0cm	6.49	3.63	2.03	1.99	0.96	0.71
0.5cm	2.78	1.84	1.11	0.99	0.73	0.52
1.0cm	1.55	1.07	0.68	0.97	0.60	0.43
1.5cm	0.97	0.65	0.43	0.79	0.55	0.39
2.0cm	0.64	0.42	0.29	0.62	0.42	0.30

the antenna and the human head, and are comparable with those found by others for other forms of low-interaction antenna. One figure is 5.7% for a printed structure on the back of the handset [3]. Other published figures [4] are 6.2% and 9.2% for a two-element array, and a two-element array with reflector and tilted elements. The latter results have only been given for 2 cm spacing, but compare well with the present figures and were obtained by a different method, namely MoM. Table 3 shows the maximum SAR for the various cases, but averaged over 1g and 10g of head tissue.

Figures 3 and 4 present the variation of the real and imaginary parts of the voltage ratio R_v for the two-element array, corresponding to minimised P_{abs} and minimised SAR_{max}, respectively, for a range of handset-sphere distances. In Figure 3 it is noteworthy that the real part is almost constant and the imaginary part is very close to zero at a distance of 1.5 cm. Thus for this particular case the feed network can be easily implemented using only a simple reactive splitter circuit, a directional coupler or any RF network which approximates to an ideal transformer. This simplification can be achieved at other values of the handset-sphere distance by varying the separation distance between the monopoles or changing the antenna geometry.

Figure 5 shows the variation of the real and imaginary parts of R_v corresponding to minimised SAR_{max}, for a range of handset-sphere distances, for a two element array with reflector. The real part still varies much less than the imaginary, but both parts vary more than in Figure 4. This contrasting behaviour is clearly due to the reflector but does not have an obvious physical explanation.

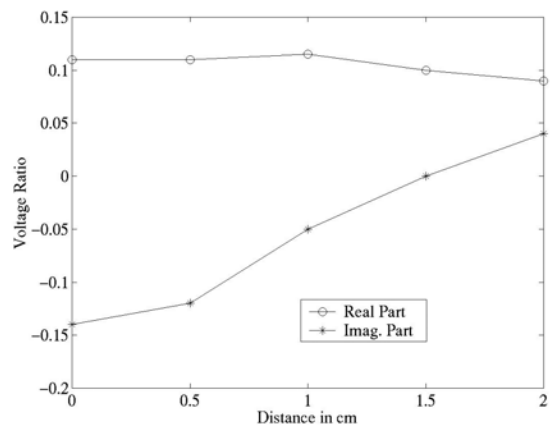


Fig. 3. The voltage ratio vs. distance d for minimised total P_{abs} of two element array.

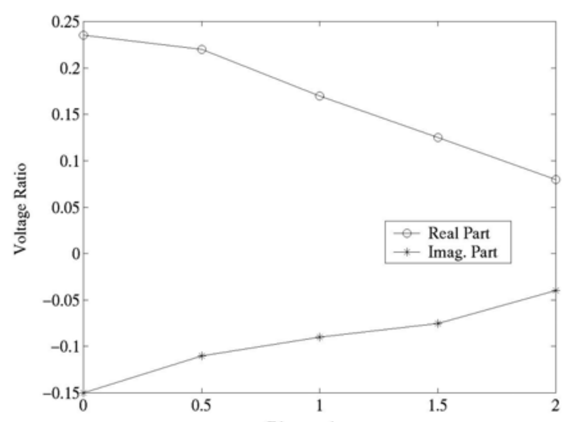


Fig. 4. The voltage ratio vs. distance d for minimised SAR_{max} of two-element array.

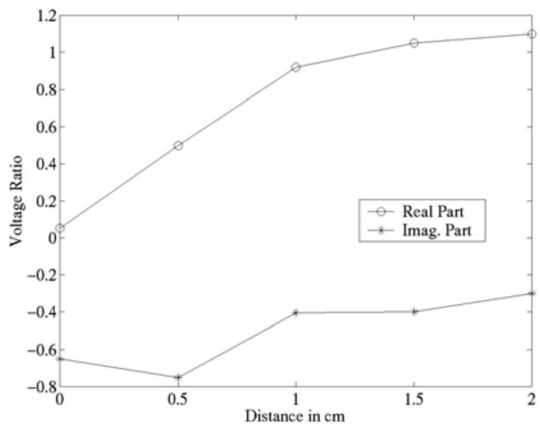


Fig. 5. The voltage ratio versus distance d for minimised SAR_{max} of two-element array with reflector.

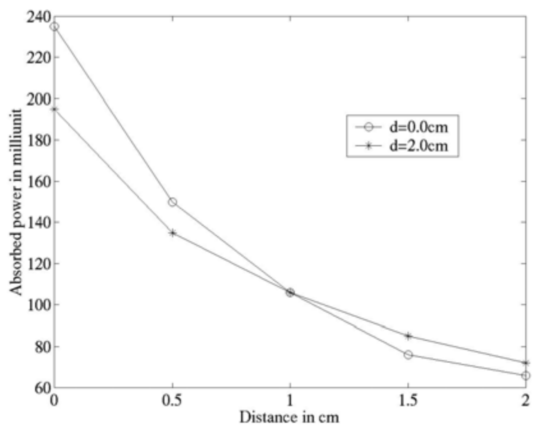


Fig. 6 Total absorbed power versus distance d using fixed voltage ratio for two-element monopole array optimised for d = 0 cm.

It would be practically difficult to change R_v adaptively to remain optimum for a variable head-antenna spacing, but it could be fixed at the optimum value for a particular spacing. The resulting dynamic range of P_{abs} and SAR_{max}, for fixed R_v and varying distances, is presented in Figures 6 and 7 respectively. For both figures, R_v values optimised for SAR_{max} at d = 0 cm and 2 cm are used. Figure 7 suggests that the former would probably be best used in practice as it gives better performance in the most critical (closest approach) condition and it is also seen to give better average performance. Figure 6 indicates that this also gives a near-optimum reduction in P_{abs} and so is probably the best practical choice without deeper knowledge of biological factors.

Figure 8 shows a contour plot of computed P_{abs} as a function of R_v for a two-element array at d=0 cm, and the optimum value can be read here or in Figure 3 as *0.106-j0.146*. Values for d = 0.5, 1, 1.5, and 2 cm have been similarly found as *0.106-j0.106, 0.107+j0.055, 0.09+j0.0*, and *0.0918+j0.0408*, respectively. Corresponding values in Figure 4, optimised for SAR_{max} are noticeably different. The improvement factors for $P_{abs,}$ using ratios optimised for this quantity and at each individual spacing, are 9.79 dB, 9.03 dB, 8.07 dB, 7.38 dB and 6.95 dB respectively. Comparing these factors with those computed using minimised SAR_{max}, the differences are fairly small, so the question of whether peak or integrated SAR is biologically more important is not crucial.

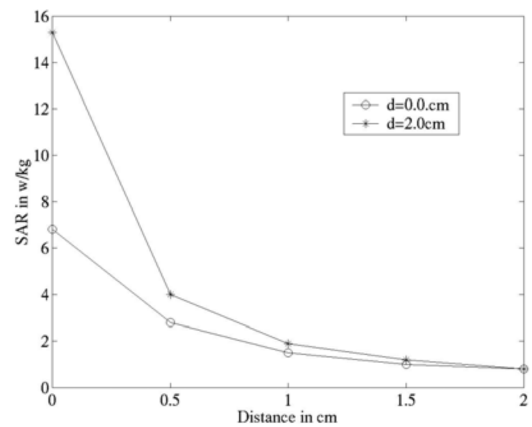


Fig. 7. SAR versus distance d using fixed voltage ratio for two element monopole array optimised for d = 0 cm.

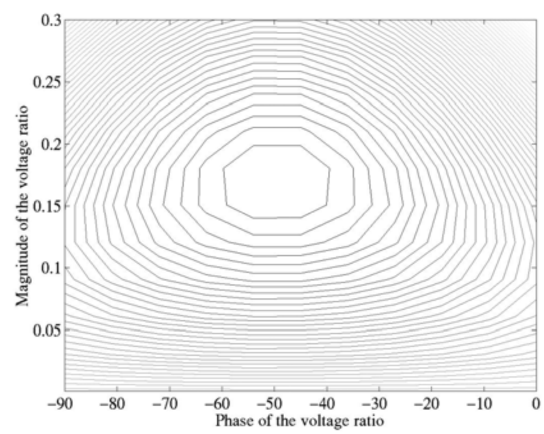


Fig. 8. Total absorbed power contours as a function of the voltage ratio of two element monopole array for d = 0.0 cm (stationary point is a minimum).

Figures 9 and 10 show the computed SAR distribution in dB over two different slices, horizontally and vertically through the spherical head, for four versions of the handset: a. single monopole; b. single monopole with reflector sheet, c. two element array, and d. two element array with reflector sheet, for d = 0 cm. It is important to note the method of normalising these plots, which is to divide values in all plots by the peak value occurring at zero distance for the monopole. Clearly, these Figures show an overall reduction and the

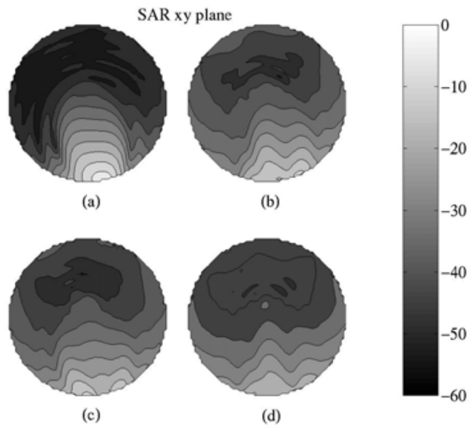


Fig. 9. SAR distributions over a horizontal cut through the sphere, at d = 0.0 cm: (a) single monopole antenna; (b) single monopole antenna with reflector sheet; (c) two element array; (d) two element array with reflector sheet.

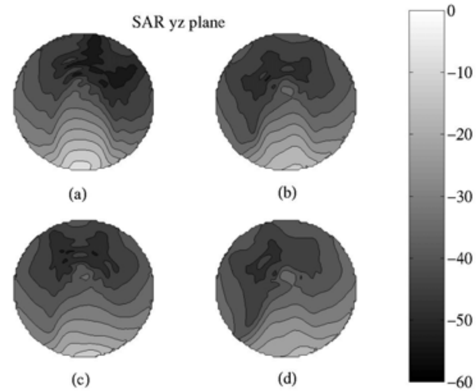


Fig. 10. SAR distributions over a vertical cut through the sphere, at d = 0.0 cm: (a) single monopole antenna; (b) single monopole antenna with reflector sheet; (c) two element array; (d) two element array with reflector sheet.

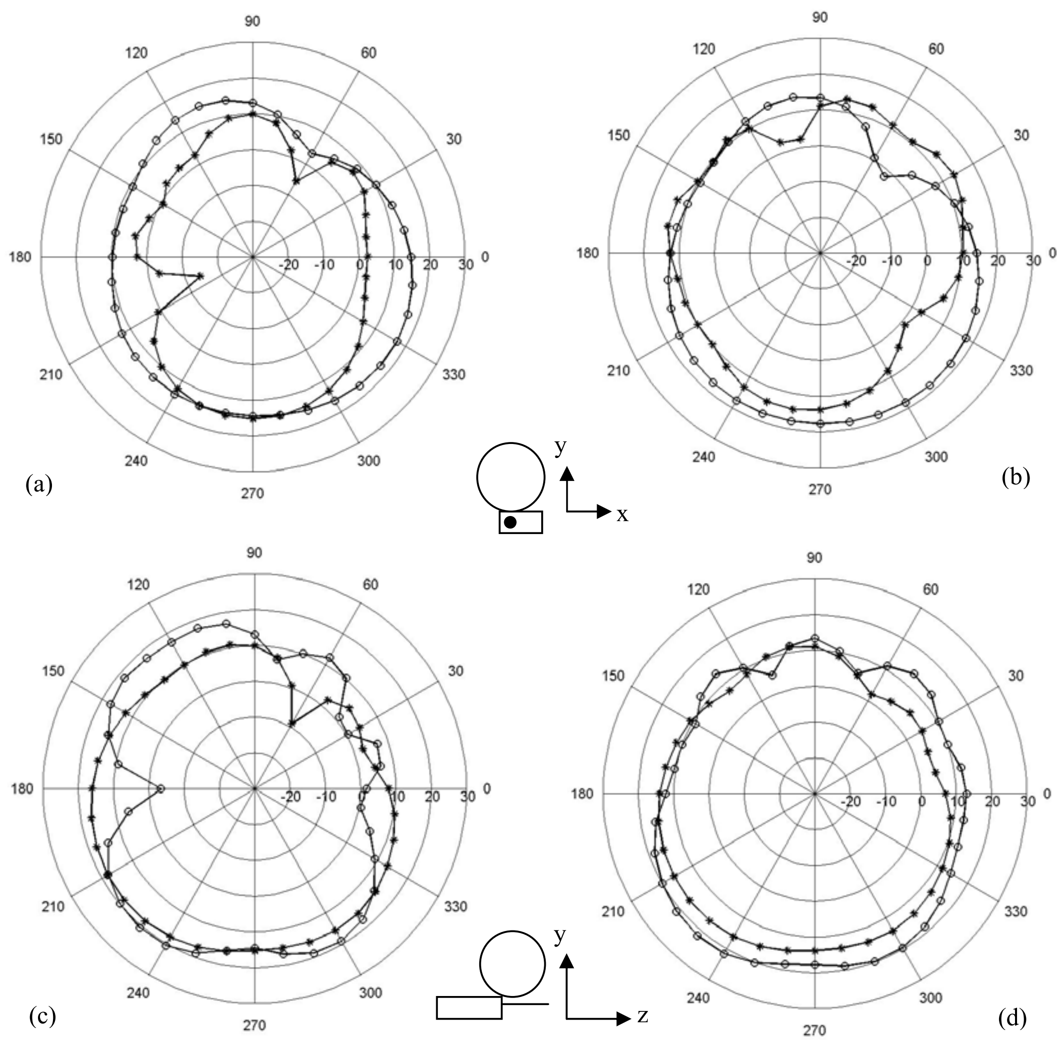


Fig. 11. Far field patterns for two different planes: (a) and (b) horizontal plane (θ =90°) for single monopole and two element array respectively; (c) and (d); vertical plane at ϕ = 90° for single monopole and two-element array, respectively; d = 0.0 cm (E_θ: ooo, E_ϕ: ∗∗∗).

improvement for the array relative to the monopole when they are at the same distance.

The spatial null in SAR towards the outer surface of the head, when the two element array antenna is used, is clearly seen. Adding a reflector sheet improves results in all cases, but the array without reflector is better than the monopole with reflector (note that the SAR distributions are asymmetric since the antennas are located towards one edge of the handset). The distributions of SAR prove to be quite similar to those obtained using the less realistic model of the antenna as two ideal dipoles [1], despite the considerable structural difference in the antenna. As expected, the realistic handset does show visible asymmetries in the distributions, whereas the dipole model has exact symmetry.

Figure 11 shows the radiated far-field patterns for two different planes and two versions of the handset, namely a single monopole and a two element array optimised for SAR_{max}. The horizontal and vertical plane pattern cuts are displayed at $\theta = 90^0$ and $\phi = 90^0$ respectively. Comparing plots (a) and (b), it is clear that the array has superior performance in terms of the power averaged over azimuth, for the dominant field component (E_θ) or for the power sum of both components, than the single monopole. This is consistent with the reduction of P_{abs} making more power available to be radiated into space.

IX. CONCLUSIONS

This work has demonstrated that a simple phased array handset antenna can be designed to protect the user from radio frequency exposure, and will have additional benefits in terms of improved overall performance. The array can be designed to produce the minimum $P_{abs,}$ the total absorbed power in the head or the smallest $SAR_{max,}$ the local spatial peak in SAR. For

the second criterion, a novel optimisation algorithm was presented which allows for migration of the location of worst SAR as the array excitation is varied. Either approach produces significant reductions in exposure and improvements in the power available for communications with a base station. The voltage ratio found for minimised SAR_{max} at the minimum distance (handset touching the simulated head) is probably the best compromise for minimising both SAR_{max} and Pabs over a wide range of separation distances of the handset from the head. An important conclusion is that the criteria of minimising the total absorbed power or the worst point value of SAR are not seriously in conflict. Optimisation for minimum SAR at another point such as the head centre could also be selected if it were believed to be biologically more sensitive. Almost certainly, more complex arrays could give greater protection, as remains to be investigated.

REFERENCES

[1] R. A. Sadeghzadeh, N. J. McEwan and M. A. Al Sabey, "Approximate modelling of head-antenna interactions using spherical wave expansions," *IEE Int. Conf. on Antennas and Propagation*, Edinburgh, pp. 249-252, 1993.

[2] J. Toftgard, S. N. Hornsleth, and J. B. Anderson, "Effects on portable antennas of the presence of a person," *IEEE Trans. Antennas and Propagation*, vol. AP-41, pp. 739-746, 1993.

[3] H. O. Ruoss, N. Berger, and F. M. Landstorfer, "Optimised slot antennas for hand held mobile telephones," *IEE Int. Conf. on Antennas and Propagation*, Edinburgh, pp. 249-252, 1997.

[4] R. A. Abd-Alhameed, N. J. McEwan, P. S. Excell and E. A. Abdulmula, "A two-element phased array antenna for mobile handsets to reduce the mutual effect with the human head," *IEE Conf. on Antennas and Propagation*, York, pp. 291-4, 1999.

[5] M. A. Mangoud, R. A. Abd-Alhameed, N. J. McEwan, P. S. Excell, and E. A. Abdulmula, "SAR reduction for handset with two element phased array antenna using hybrid MOM/FDTD technique," *Electronics Letters*, vol 35, no. 20, pp. 1693-1694, 1999.

[6] N. J. McEwan, B. A. W. Ibrahim, R. A. Sadeghzadeh, E. A. Abdulmula, and K. A. Qassim, "Pattern Shaping for Handset Antennas," *IEE 9th International Conference on Antennas and Propagation*, IEE Conf. Pub1. no. 407, Eindhoven, pp. 106-110, 4-7 April 1995.

[7] E. A. Abdulmula, "Improved Handset Antennas for Personal Communications at 1.8 GHz," PhD Thesis, University of Bradford, UK, 2000.

[8] R. A. Sadeghzadeh and N. J. McEwan, "Antenna design considerations for personal communications user protection," *IEEE 45th Vehicular Technology Conference*, vol. 2 pp. 844-847, 1995.

[9] E. A. Abdulmula, N. J. McEwan, and R. A. Sadeghzadeh, "Phased Array Antennas for personal communications Handset," High frequency postgraduate student colloquium, University of Leeds, pp.112 -117, 1997.

[10] M. A. Al-Sabey, "Spherical wave expansion for scattering by a sphere at a finite distance from a dipole source," MSc Dissertation, University of Bradford, UK, 1992.

[11] R. A. Sadeghzadeh, N. J. McEwan and M. S. Abrishamian, "Improved modelling of head-antenna interactions using spherical wave expansions," *2nd International Conference on Computation in Electromagnetics*, Nottingham, Uk, IEE Conf. Pub1. 384, pp. 95-98, 12-14 April 1994.

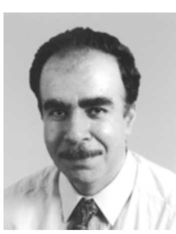
[12] P. S. Excell and R. A. Abd-Alhameed, "Experience of antenna simulation using NEC, FDTD and a novel moment method," *IEE Colloquium on High Frequency Simulation in Practice*, London, pp. 8.1-8.4, 1997.

[13] K. W. Kim and Y. R. Samii, "EM Interactions between handheld antennas and human: anatomical head vs. multi-layered spherical head," *Antennas and Propagation for Wireless Communications, IEEE-APS Conference*, pp. 69-72, 1-4 Nov.1998.

[14] V. F. Perez et al, "Analysis of proposals to reduce SAR levels from GSM Terminals," *IEEE MTT-S Digest*, pp. 2227 – 2230, 2001.

Jinan Moustafa was born in Mosul, Iraq. She received the BEng.(Hons.) degree in Electronic and Electrical engineering and MPhil degree from University of Bradford , UK, in 1995 and 1997 respectively. Her research field for the MPhil degree was in coplanar waveguide based antennas for broadside radiation and circular polarisation. Later as a Research Assistant she was involved in projects on printed antennas and reduction of harmonic radiation from an active microstrip patch antennas. Currently, she is working toward the PhD degree at the University of Bradford. Her main research has been in use of FDTD techniques for simulating the user interaction of mobile telephones employing different phased array and balanced antennas.

Neil J McEwan was born in London, U.K. in 1948. He received the BA degree in mathematics from Cambridge University, U.K. in 1969, and the PhD degree in radio astronomy from Manchester University, U.K. in 1975. Since 1998 he has been a Principal Research Engineer with Filtronic PLC at Shipley, U.K., having previously been Reader in Electromagnetics in the Department of Electronics and Telecommunications, University of Bradford, UK. He has previously worked on microwave propagation in the troposphere, and was involved in propagation experiments using the ATS-6 and European OTS satellites. More recently he has worked on various aspects of active and passive antennas. He spent the year 1987 with Millitech Corporation, MA, as Visiting Research Scientist. Dr McEwan is a member of the Institution of Electrical Engineers.



Raed A. Abd-Alhameed was born in Basrah, Iraq in 1959. He received the B.Sc. and M.Sc. degrees from Basrah university, Iraq, in 1982 and 1985 respectively, and the Ph.D. degree from the university of Bradford, UK, in 1997, all in electrical engineering. From 1997 to 1999 he was a Postdoctoral Research Fellow at the university of Bradford, specialisation in computational modelling of electromagnetic field problems, microwave nonlinear circuit simulation, signal processing of preadaption filters in adaptive antenna arrays and simulation of active inductance. From 2000 to 2003 he has been a lecturer in the University of Bradford. Since August 2003 he was appointed as a senior lecturer in applied Electromagnetics in the same University. His current research interests include hybrid electromagnetic computational techniques, antenna design, low SAR antennas for mobile handset, RF mixers and active antennas. Dr Abd-Alhameed is a member of the Institution of Electrical Engineers and Institution of Learning and Teaching for Higher Education.

Peter Excell is Professor of Applied Electromagnetics and Associate Dean for Research in the School of Informatics at the University of Bradford, UK, where he has worked since 1971. He obtained his BSc in Engineering Science from the University of Reading in 1970 and his PhD from the University of Bradford in 1980 for research in electromagnetic hazards. His research interests cover computational electromagnetics, EMC, antenna design, bioelectromagnetics and mobile applications: he has published over 200 papers and he holds three patents. He is a Senior Member of the Institute of Electronics and Electrical Engineers, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer.