Approximation of EMF spatial distribution near mobile phone in order to form a "virtual" antenna array

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Abstract. Article describes the methods of approximation of electromagnetic field spatial distribution, which spatial samples are measured using an annular antenna array located near scatterer with a priori unknown geometry and material properties. As example, case of mobile phone located at user's head were studied. The model of the human head and hand was simulated as a layered structure, the outer layer imitated the skin, and water was used as the inner filling. The study results show good performance of modified method of forming a "virtual" antenna array, which can significantly reduce the field approximation error, thereby making it possible to successfully predict the electromagnetic field phase structure at distances exceeding the radius of the used antenna array by three times. Proposed method can significantly increase the efficiency of subspace methods of direction finding and methods of adaptive signal processing in multichannel systems (in particular, the MIMO) due to the multiple increase in the number of virtual channels which are functionally equivalent to additional real channels, and also - increasing the electrical dimensions of the antenna system ("virtual" antenna array).

1. Introduction
The user's body has a significant impact on the functioning of receiving antenna system of a mobile phone, caused by scattering and absorbing electromagnetic waves as a result of which spatial structure of the measured electromagnetic field is distorted. It is obvious that due to the a priori uncertainty of the geometric parameters and material properties of the user's body the calibration of mobile phone antenna system, considering the influence of the scatterer, is impossible. We also note the complexity of scatterer morphology which is the user's body.

Another important aspect is that size of antenna array is limited by the size of a mobile phone's body. That is why problem of developing a method that can reduce or even completely eliminate negative impact of nearby scatterers on radio monitoring and radio direction finding systems, without using any information about geometry of scatterers or their electrodynamic properties, is very actual task. The result of using these methods should be a significant increase in resolution of the complexes, reducing errors in DOA estimation, and eliminating blunders.

Practical application of the methods is to use the data on spatial distribution of total (incident and scattered waves) field, measured by a physically existing radio direction-finding antenna system, to form a “virtual” antenna array (VAA) which is a system of spatial samples of complex amplitudes of the recorded field. Using this array, it is possible, by calculating the corresponding direction-finding characteristic, to significantly increase accuracy of DOA estimation and angular coordinates resolution of radio monitoring complexes of mobile, airborne, and stationary bases.
The use of the virtual antenna arrays apparatus for radar-location is of particular interest, such an application is considered in a number of studies [1-4]. In works [1-3] antenna arrays are considered, in which an additional virtual antenna array is formed, which allows to improve the characteristics of the considered antenna system; in [4] mathematical algorithms that allow improving the antenna system characteristics are considered.

It should be noted that scope of these methods’ applicability is not limited to radio direction finding tasks. In this paper, the possibility of using the methods of approximating structure of measured electromagnetic field in cellular communications equipment in case of a mobile phone receiving system is considered and studied.

2. Methods of “virtual” antenna array formation

These methods are based on hypotheses about the possibility of representing a field on an antenna array contour using the theory of methods of analytic functions of a complex variable \( z = x + i \cdot y \), in particular, the Cauchy integral or the Laurent series [5]. In this case, the amplitude-phase distribution of the field on the elements of \( N \)-element antenna array can be considered as samples \( U_n = U(\phi_n) \) \( (\phi_n = 2\pi(n - 1)/N, n = 1,2,\ldots,N) \) of periodic function \( U(\phi) \) with period of \( 2\pi \) describing the continuous distribution of the field around a circle of radius \( R \) (\( R \) - is radius of the antenna array) taken through the intervals \( 1/(2F) \) (where \( F = 1/(4\pi N) \)). In turn, function \( U(\phi) \) can be represented as a Kotelnikov series:

\[
U(\phi) = \sum_{n=-\infty}^{\infty} U_n \frac{\sin(2n\pi(\phi-\phi_n))}{2\pi F(\phi-\phi_n)}.
\]

Then use the decomposition of function \( U_{AP}(z) = U(\phi) \) in ring \( R - \delta \leq r \leq R + \delta \) (where \( \delta << R \)) in the Laurent series:

\[
U_{AA}(z) = \sum_{k=-\infty}^{\infty} c_k z^k,
\]

where \( c_k = \frac{1}{2\pi i} \int_{C} \frac{U(\zeta)}{\zeta^{k+1}} d\zeta \). After that, the derivatives of function \( U_{AP}(z) \) are found in the radial directions \( \partial U(\phi, r)/\partial r, \partial^2 U(\phi, r)/\partial r^2 \) etc., and values of function \( U_{VAA}(\phi, R + L) \) are estimated using a segment of the Taylor series:

\[
U(\phi, R + L) \approx U(\phi, R) + L \cdot \partial U(\phi, r)/\partial r + 0.5L^2 \cdot \partial^2 U(\phi, r)/\partial r^2 + ...
\]

However, the approach described above are applicable only in case of sufficiently small electrical dimensions of region where VAA is formed.

Other methods are following directly from the principles of electrodynamics. In particular, from the Lorentz Lemma, according to which it is possible to calculate all field components in volume \( V \) bounded by closed surface \( S \) if the tangent field components are known on a given surface [6]. The scalar analogue of the Lorentz lemma is the expression for the Kirchhoff integral, which allows to calculate the field at any point of volume \( V \) if values of the field and its normal derivative are known on closed surface \( S \) bounding given volume. In this case, it is possible to move from a volume problem to a flat one.

In addition, it is possible to represent the amplitude-phase distribution on elements of real antenna array (RAA) using expression:

\[
E_{xn} = E_x(x_n, y_n) =
\]

\[
= \sum_{m=1}^{M} B_m \cdot \left( \exp \left( -ik_0 \sqrt{(x_n - x_m^q)^2 + (y_n - y_m^q)^2} \right) \right) / \sqrt{(x_n - x_m^q)^2 + (y_n - y_m^q)^2},
\]

where \( x_n, y_n; n = 1,2,\ldots,N \) - N-element AA coordinates; \( x_m^q, y_m^q; m = 1,2,\ldots,M \) - coordinates of M points auxiliary sources; \( \vec{B} = [B_1, B_2, \ldots, B_M]^T \) - complex amplitude vector of auxiliary sources; \( k_0 = 2\pi/\lambda \) - free space wave number; \( \lambda \) - free space wavelength; \( M_{n,m} = \exp \left( -ik_0 \sqrt{(x_n - x_m^q)^2 + (y_n - y_m^q)^2} \right) / \sqrt{(x_n - x_m^q)^2 + (y_n - y_m^q)^2} \) - matrix \( N \times M \).
elements of which depend on frequency and coordinate values of elements of the antenna array and auxiliary point sources. In this case \(N = M\), therefore, the matrix is square.

However, authors of this article found out that the most promising method of VAA generation is the method using the pseudo-solution procedure, in which \(N\) is not equal to \(M\). In this case, vector of the complex amplitudes of the auxiliary sources calculated as \(\vec{B} = (M^H \cdot M)^{-1} \cdot M^H \cdot \vec{U}\), where \(\vec{U}\) is vector of the complex amplitudes of elements of the physically existing antenna array.

3. Research and results

The authors researched the possibility of using the VAA formation methods based on the pseudo-solution search procedure for approximating the phase structure of the electromagnetic field near handset antenna system and user’s head. The electromagnetic field of the incident wave was measured at 18 points, located equidistantly along a circle with radius of \(R_{AA} = 15\) mm near the surface of the phone. These field readings were taken as samples measured by the telephone antenna system. In addition, on circles with radius of \(R_1 = 22.5\) mm, \(R_2 = 30\) mm, \(R_3 = 45\) mm, also at 18 equidistant points, complex amplitudes of the E component of electromagnetic wave were measured. The human head model was presented as a layered structure imitating skin, bone and human brain [7]. The phone model was represented as an ideal metal parallelepiped with dimensions of 100×40×18 mm, Fig. 1.

Front of electromagnetic wave was directed from the face of the user, and vector \(E\) was parallel to the vibrators.

**Figure 1.** Location of spatial samples in which EMF was recorded relative to the mobile phone casing.

Using the complex amplitudes measured at radius \(R_3\), and the pseudo-solution procedure described above, the phase values at the corresponding points on circles \(R_2, R_3\) were predicted. Fig. 2 and Fig. 3 show graphical dependencies of the predicted phases. The circles indicate the phases in each of \(K\) points measured experimentally, diamonds – indicate the phases obtained during the approximation. In addition, the table 1 presents numerical values of errors (maximum and average) within the studied frequency bands.
Figure 2. Phase values at points within radius of $R_1 = 22.5$ mm at a) $f = 900$ MHz, and b) $f = 1800$ MHz.

Figure 3. Phase values at points within radius of $R_2 = 45$ mm at a) $f = 900$ MHz, b) $f = 1800$ MHz.

| Table 1. Approximation of error values |
|----------------------------------------|
| Radius, mm | Error type | Frequency range, MHz |
|            |            | 890-915 | 935-960 | 1710-1785 | 1805-1880 |
| 22,5 | Max. | 4,6° | 4° | 4,8° | 5,7° |
| Avg. | 2,1° | 2,3° | 1,8° | 2,2° |
| 30 | Max. | 6,4° | 6° | 7,9° | 8,9° |
| Avg. | 2,2° | 2° | 2,9° | 3,4° |
| 45 | Max. | 9,3° | 8,6° | 16,8° | 17,3° |
| Avg. | 3,8° | 3,7° | 6,3° | 6,5° |

4. Conclusion
As can be seen from the data presented above, the VAA formation method can quite successfully approximate phase structure of electromagnetic field at distances up to three times the radius of antenna array which was receiving electromagnetic wave. The approximated complex amplitudes of
the field can be interpreted as elements of a hypothetical “virtual” antenna array and used for adaptive processing of received information: estimating the angular coordinates of radio emission sources, suppressing interference, increasing the signal-to-noise ratio at receiver input, increasing angular coordinate resolution. A key feature of the method is absence of the need in any information about scatterer (user’s body) and high efficiency of its implementation in a portable computer system of real-time processing.

It should be noted that use of proposed method can significantly increase efficiency of applying the methods of super resolution of radio emission sources and methods of adaptive signal processing in multichannel systems (in particular, MIMO systems) due to the possibility of a significant increase in the number of virtual channels functionally equivalent to additional real channels, and also - an increase in the electrical size of the antenna system (“virtual” antenna array).

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