Suppression of EM Fields using Active Control Algorithms and MIMO Antenna System

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***Abstract**. Active methods for attenuating acoustic pressure fields have been successfully used in many applications. In this paper we investigate some of these active control methods in combination with a MIMO antenna system in order to assess their validity and performance when applied to electromagnetic fields. The application that we evaluated in this paper is a model of a mobile phone equipped with one ordinary transmitting antenna and two actuator-antennas which purpose is to reduce the electromagnetic field at a specific area in space (e.g. at the human head). Simulation results show the promise of using the adaptive active control algorithms and MIMO system to attenuate the electromagnetic field power density.*

Keywords

Electromagnetic fields, adaptive active control algorithms, multiple-input multiple-output (MIMO) antenna systems, radio wave propagation.

1. Introduction

Active suppression of noise and vibrations is a well-established field of research with many applications in acoustic and mechanical industries [1] – [3]. The method of canceling out a signal comes from the principle of superposition. If two signals are superimposed, they will add either constructively or destructively. The objective of our study is to investigate the possibility of applying these adaptive active control methods with the aim of lowering the electromagnetic field power density at a specific area in space using the superposition principle and a MIMO (Multiple Input Multiple Output) antenna system.

There have been several studies done, with conflicting results, on the effects of cell-phone radiation on the human body. The amount of radiation emitted from most cell phones is very minute. However, given the close proximity of the phone to the head, it is entirely possible for the radiation to cause harm. This paper makes a contribution to that discussion by proposing a new approach by exploiting adaptive active control algorithms combined with a MIMO antenna system to attenuate the electromagnetic field at specific area. Thus, the application we evaluated in this paper is a model of a mobile telephone equipped with one ordinary transmitting antenna and two actuator-antennas which purpose is to reduce the electromagnetic field at a specific area in space (e.g. at the human head). It is worth stressing at this point that the purpose of this MIMO system is not to improve the capacity or quality of transmission between the mobile unit and base station, but to predict the channel response or sense the radiated field that can then be controlled by using the active control algorithms. The modeling of the antenna elements and the electromagnetic field calculations are done in FEMLAB. This modeling software is also used in combination with MATLAB to implement the adaptive algorithms used to control the electromagnetic field.

The organization of this paper is as follows. In Section 2, we present the FEMLAB MIMO antenna model. In Section 3, the adaptive algorithms used to suppress the power density of the electromagnetic field are briefly presented. Simulation results are shown in Section 4. Finally, Section 5 concludes the paper and presents further research ideas.

2. The FEMLAB MIMO Model

The application used in this paper is a two-dimensional (2D) cross-section model of a physical system consisting of eight vertically polarized antenna elements and of a human head phantom, as shown in Figs. 1 and 2, respectively. The operating carrier frequency of the model is 900 MHz (a wave length of approximately 0.33 m). The simulation of the radio waves is performed numerically by using the finite element method (FEM) in FEMLAB for solving the electromagnetic field equations. FEMLAB is an interactive environment for modeling and simulating scientific and engineering problems based on partial differential equations (PDE) that are the basis for the laws of science. One of the FEMLAB applications is to solve the electromagnetic field equations.

In a simple source-free medium $\nabla \cdot \mathbf{E} = 0$ we can combine *Maxwell's* equations in time-harmonic form to get the inhomogeneous *Helmholz's* equation:

$$\nabla^2 \mathbf{E} + \omega^2 \varepsilon\mu \mathbf{E} = -j\omega\mu \mathbf{J} \ , \qquad (1)$$

where **J** is the current density input to the transmitting antennas and **E** is the electric field. To simplify the equations we have omitted the arguments of the different fields; e.g. **E** is defined as $\mathbf{E}(x,y)\exp(j\omega t)$. The parameters denoted by ε, μ and σ define the electromagnetic properties of the different materials in the model; these parameters can change in both time and space, but in this paper we assume them to be real valued constants. To model materials that contain both conductive and dielectric properties, a complex valued parameter ε_C is defined:

$$\varepsilon_c = \varepsilon_r - j\sigma/(\omega\varepsilon_0)\ , \qquad (2)$$

where σ is the conductivity and ε_r is the relative permittivity of the material when there is an incident time-harmonic wave with an angular frequency ω.

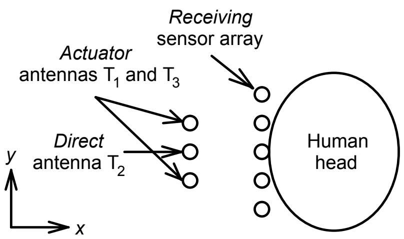


Fig. 1. 2D model representing the tested physical system.

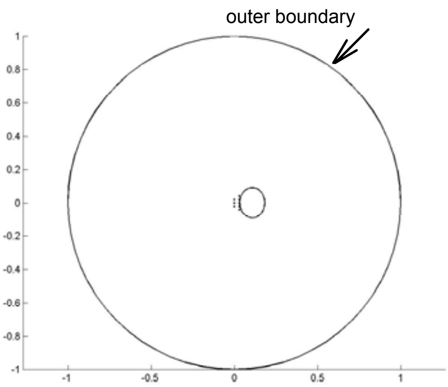


Fig. 2. The FEMLAB representation of the 2D model in Fig 1. The outer boundary is set to a radius of 1 meter to limit the FEM solution.

The antenna elements in this model are assumed to be made out of copper and have the following electric properties:

$\varepsilon_r = 1$, since this is not a dielectric material,
$\sigma = 5.99 \cdot 10^7$ [S/m].

To electrically model the human head is a more complicated task since it consists of organic tissues of varying electric properties. For simplicity, an average of the electric properties of the brain and skull at a frequency of 900 MHz is used here:

$\varepsilon_r = 45.805496$,
$\sigma = 0.766504$ [S/m].

These values are based on the 4-Cole-Cole equation as described in [4]. Since there are no ferromagnetic materials in this FEM model, it will be sufficient to set the permeability equal to the free space permeability $\mu = \mu_0$.

The finite element method requires that the modeled area is finite and therefore it needs an outer boundary as is clearly shown in Fig. 2. In the model we are using a very simple absorbing boundary condition to approximately account for the radio waves propagating towards infinity:

$$\mathbf{n}\cdot\left[\nabla\mathbf{E}_z\right] - \left[\omega\sqrt{\left(n_x^2+n_y^2\right)\ \varepsilon\mu}\right]\ \mathbf{E}_z = 0\ . \qquad (3)$$

FEM solution of electric field $\mathbf{E}_z(x,y)$ in this confined 2D room is then used to calculate the *Poynting* vector $\mathbf{S}(x,y)$ and the power density $|\mathbf{S}(x,y)|$, which is plotted in Fig. 3.

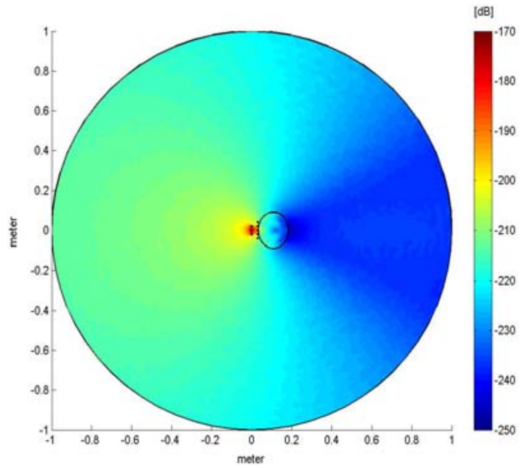


Fig. 3. A surface plot showing the calculated magnitude of the power density based on the electric field solution.

To reduce the electromagnetic field within a certain area in the FEM-modeled space, a MIMO radio channel is modeled in order to compensate for the spatial displacement. In this paper FEMLAB is used to simulate the physical MIMO antenna system, which in this case consists of 3 transmitting antennas and 5 receiving antennas as shown in Fig. 1. The spacing between the antenna elements used in this application is 0.02 m $<< \lambda$; thus this arrangement can not be seen as an ordinary beamformer as the antenna elements are working in the radiated near-field. The input signals to this system are three separate currents in a complex-valued phasor notation, one for each transmitting antenna. The simulated output current from the 5 receiving antennas form complex-valued data vector $\mathbf{e} = [e_1\ e_2\ e_3\ e_4\ e_5]^T$ denoted as the error signal vector of the system. The centre antenna T_2 (Fig. 1) is transmitting the signal that we want to cancel (it acts as the antenna on any ordinary mobile telephone) and the two flank transmitter antennas T_1 and T_3 (Fig. 1) are denoted as actuator-antennas, which will be used to reduce the signal from the antenna T2 at some specified area.

Since the model is experimentally confirmed to be linear [5], and this is a weak-stationary problem with a monochromatic time-harmonic signal, it is sufficient to describe the parameters as a 5×3 complex-valued matrix **H**. These complex-valued numbers describe the frequency response between the different combinations of transmitting and receiving antennas.

$$\mathbf{H} = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) & H_{13}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) & H_{23}(\omega) \\ H_{31}(\omega) & H_{32}(\omega) & H_{33}(\omega) \\ H_{41}(\omega) & H_{42}(\omega) & H_{43}(\omega) \\ H_{51}(\omega) & H_{52}(\omega) & H_{53}(\omega) \end{bmatrix}. \quad (4)$$

Partitioning the matrix **H** into two separate matrices: $\mathbf{F} = [\mathbf{H}_1\ \mathbf{H}_3]$ for describing the actuator-antennas channel and $\mathbf{g} = \mathbf{H}_2$ for describing the objective antenna channel, where $\mathbf{H}_m$ represents a column vector *m* of matrix **H**. The system can now be described as consisting of two separate channels as depicted by blocks **g** and **F** in Fig. 4, in which case the vector **g** (the *direct* channel) channels the "*Transmitted objective signal*" *s* and the matrix **F** (the *forward* channel) channels the "*actuator-signals*" **x**, which is controlled by the adaptive filter **w**. The vector **e** is the residual error signal.

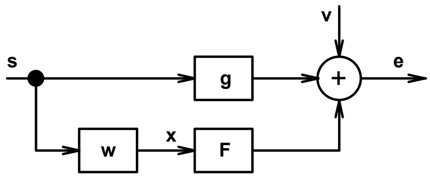


Fig. 4. Model of the direct channel **g**, and the forward channel **F** controlled by the filter **w**.

With the additive white Gaussian noise (AWGN) signal **v** included in the system, the residual error signal **e** can be expressed in matrix form as:

$$\mathbf{e} = s\,\mathbf{g} + s\,\mathbf{F}\,\mathbf{w} + \mathbf{v}\ , \quad (5)$$

where **w** is the filter vector which consists of one complex-valued filter weight for each actuator-antenna, $\mathbf{w} = [w_0\ w_1]^T$.

3. The LMS Solution and Adaptive Suppressions Algorithms

To get the best possible attenuation in energy sense at the receiving antenna array (and indirectly in the human head), the total energy output ξ of the error signal **e** must be as low as possible. One way of achieving this task is by incorporating a complex-valued filter **w** in front of the *forward* channel as shown in Fig. 4. If it is assumed that **w** is linear and the noise as AWGN, then the minimum residual mean energy of the error signal can be expressed as:

$$\min_{\mathbf{w}} \xi = \min_{w} \mathrm{E}\left\{|\,\mathbf{e}\,|^2\right\} = \min_{\mathbf{w}}\ \mathrm{E}\left\{\mathbf{e}^{\mathrm{H}}\mathbf{e}\right\} \quad (6)$$

If the input signal *s* and the noise vector **v** are assumed to be uncorrelated then the mean energy of the residual error signal can be written as:

$$\xi = \mathrm{r_g} + \mathbf{w}^{\mathrm{H}}\mathbf{p} + \mathbf{p}^{\mathrm{H}}\mathbf{w} + \mathbf{w}^{\mathrm{H}}\mathbf{R}_{\mathrm{F}}\mathbf{w} + \mathrm{r_v} \quad (7)$$

where **p** represents the crosscovariance between the *direct* channel and the *forward* channels, $\mathbf{R}_F$ is the covariance of the *forward* channels ($\mathbf{R}_F = s^*\ \mathbf{F}^H\ \mathbf{F}\ s$), r_g and r_v are the energy of the signal and noise, respectively.

The minimum value point ξ_{min} is obtained with the complex filter weight solution $\mathbf{w}_{opt}$ defined by:

$$\mathbf{w}_{\mathrm{opt}} = -\mathbf{R}_{\mathrm{F}}^{-1}\mathbf{p}\,. \quad (8)$$

This is the *Least Mean Square (LMS)* solution to the problem and is the optimal solution in mean energy sense. This solution is used as a benchmark for comparing the performance of the adaptive algorithms. In this paper we present two *Filtered-X (FX)* adaptive algorithms: the *FX Normalized LMS (FX-NLMS)* and *Actuator Individual FX-NLMS*, which weight updating equations are defined by:

$$\mathbf{w}_{\mathrm{n+1}} = \mathbf{w}_{\mathrm{n}} - \left(\frac{\beta}{trace\,(\mathbf{R_F}) + \zeta}\right)\mathbf{x}_n^H\mathbf{e}\ , \quad (9)$$

$$\mathbf{w}_{\mathrm{n+1}} = \mathbf{w}_{\mathrm{n}} - \left(\frac{[\beta_1\ \beta_2]}{diag\,(\mathbf{R_F})}\right)\mathbf{x}_{\mathrm{n}}^{\mathrm{H}}\mathbf{e}\ , \quad (10)$$

where the β's denote step-size parameters. These algorithms were chosen because of their ability to handle non-stationary signals, and they also provided the best compromise between complexity and performance. Interested readers are referred to [1-3] for more general information about these algorithms and [5, 6] for many other adaptive algorithms we have tested for this application.

4. Simulation Results

In this section we show the results of the simulations of NLMS and Actuator Individual NLMS adaptive algorithms and their effectiveness in controlling the electromagnetic field using FEMLAB-MIMO model. We have also included the result of using a single transmitting antenna only which is used as a reference level for comparison purposes in Fig. 5.

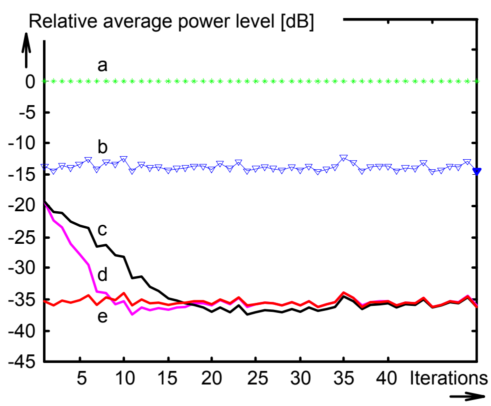
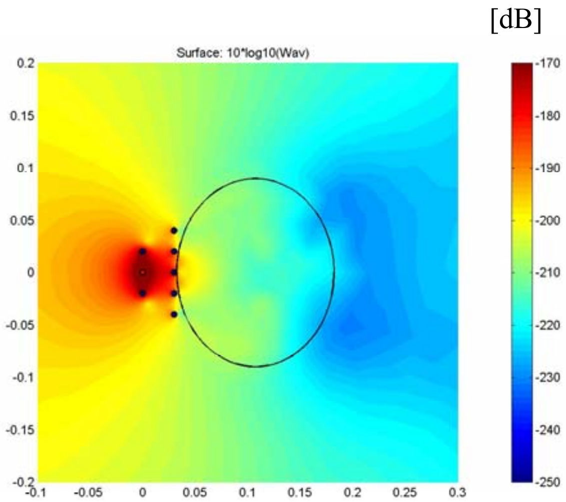


Fig. 5. The relative average power level inside the human head: (a) one transmitting antenna only, (b) 5 passive reflector elements, (c) FX-NLMS, (d) Actuator Individual FX-NLMS, (e) Least Mean Square solution.

This figure clearly shows that the amount of attenuation achieved by the least mean square solution is approximately 36 dB relative to the power level produced by a single antenna system (i.e., by using the direct transmitting antenna (see Fig. 1) only). It is clear from Fig. 5 that the adaptive algorithms after convergence give about 23 dB more attenuation compared to using the five receiving antenna elements as a passive reflector. It can also be seen that the Actuator Individual NLMS is converging about 40% faster than the NLMS towards the least mean square solution since each diagonal element of the covariance matrix is normalized separately as shown in equation (10).



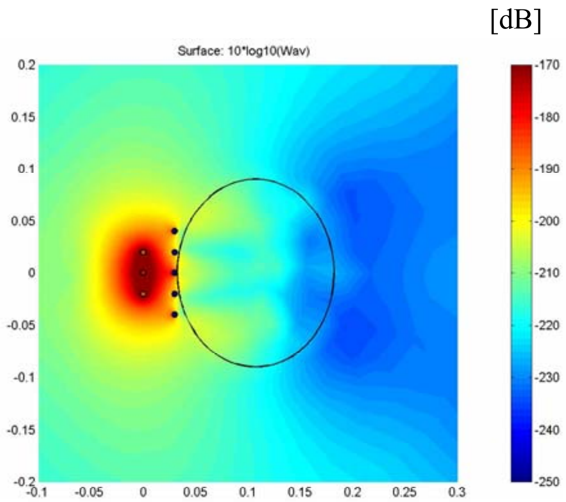


Fig. 6. Graphical plots showing the power density inside the human head phantom before (top figure) and after (bottom figure) the Least Mean Square solution is applied, which respectively corresponds to plots b and e in Fig. 5.

In Fig. 6 we show the power density field for one transmitting antenna with five passive reflector elements, and three transmitting antennas tuned to the least mean square solution (i.e., the adaptive algorithms after convergence), respectively. Evidently, the electromagnetic power density field inside the head is lower in the adaptive algorithms case. These initial results show the possibility of using MIMO antenna system for lowering the electromagnetic field power density, but further research is still needed.

5. Conclusions

In this paper we have presented a FEMLAB model that solves the PDE of an electromagnetic field and simulates the physical MIMO antenna system that is controlled by various adaptive signal processing algorithms in order to suppress the electromagnetic field at a certain area in this modeled 2D space. The attenuation level achieved from this model suggests the possibility of using an active antenna MIMO system for this purpose, but further research is still needed. Future work comprises of investigating the overall radiation efficiency and constraining the total output power of the system. It is also interesting to investigate the effect of the size and spacing of the MIMO antenna system on the overall attenuation level.

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