The Effects of MIMO Antenna System Parameters and Carrier Frequency on Active Control Suppression of EM Fields

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Abstract. *In this paper we propose a new approach employing adaptive active control algorithms combined with a Multiple-Input Multiple-Output (MIMO) antenna system to suppress the electromagnetic field at a certain volume in space (e.g., at the human head). We will investigate the effects of the size and number of MIMO antenna elements on the system performance and test the algorithms at different carrier frequencies (e.g., GSM bands and UMTS).*

Keywords

Electromagnetic fields, Adaptive Active Control Algorithms, Multiple-input multiple-output (MIMO) antenna systems, radio wave propagation.

1. Introduction

There have been several studies performed, with conflicting results, on the effects of cell-phone radiation on the human body. The amount of radiation emitted from most cell phones is minute. However, given the close proximity of the phone to the head, it might be possible for the radiation to cause harm. If you want to be on the safe side, the easiest way to minimize the radiation you are exposed to is to place the antenna as far as possible from your head. Utilizing a hands-free kit, a car-kit antenna or a cell phone whose antenna is even a couple of inches farther from the head can do this most effectively. This paper makes a contribution to that discussion by proposing a new approach by employing adaptive active control algorithms combined with a Multiple-Input Multiple-Output (MIMO) antenna system to suppress the electromagnetic field at a certain volume in space.

Active control methods for attenuating acoustic pressure fields have been successfully used in many applications [1-3]. In our initial work [4] we presented different active control signal processing algorithms (e.g., the FX-LMS, FX-NLMS, FX-Newton/LMS and Actuator Individual FX-LMS [1-3]) for use in electromagnetic field suppression. In addition, in a previous paper at Radio Engineering Journal [5] we have extended the application of these active noise control methods in a novel application and demonstrated by analysis and simulations the possibility of attenuating the electromagnetic field power density by superimposing two secondary fields over the original electromagnetic field. This requires that we transmit phase shifted copies of the signal. We have shown that by using these adaptive methods in a simulation we can achieve an extra 23 dB's of attenuation compared to using a passive reflector only.

The antenna system and the ambient environment are modeled using FEM (Finite Element Method) analysis. To compensate for the antenna displacements the system was modeled and processed as a MIMO-system controlled by a class of algorithms known as Filtered-X adaptive techniques [1-3]. The modeling of the antenna elements and the electromagnetic field calculations were performed in FEMLAB (now COMSOL Multiphysics™). This software program is also used in combination with MATLAB to implement the adaptive algorithms used to control the electromagnetic field.

In this paper we extend our previous work [5] and investigate and analyze the optimal number and placement of the MIMO antenna array system, and assess the performance at frequencies used by the GSM and UMTS standards.

The organization of this paper is as follows. In Section 2, the FEM MIMO antenna model is introduced and analyzed. In Section 3, we present the optimal least squares solution and briefly review the different adaptive algorithms used to suppress the power density of the electromagnetic field. Simulation results investigating the effects of the different MIMO antenna system parameters including the operating frequency are analyzed and presented in Section 4. Finally, Section 5 concludes the paper and presents further research ideas.

2. The FEMLAB MIMO Model

The purpose of this paper is to investigate in more detail the possibility of attenuating the electromagnetic field inside a human head when holding a mobile telephone next to the ear. In the earlier work [5] we have demonstrated the possibility of achieving realistic electromagnetic field attenuation by using adaptive control algorithms combined with a MIMO antenna array system. The simple 2D model that has been used for this purpose can be seen in Fig. 1. This model implements a numerical method known as FEM (Finite Element Method) to calculate and analyze the propagation of electromagnetic waves in the model.

The investigations in the previous work [4, 5] were carried out in the frequency domain at a frequency of 900 MHz. The input signal to the model is the current in each of the transmitting antenna elements (the Direct and Actuator antennas, see Fig. 1). The current is modeled as a complex valued phasor representation. In this simple model we assume that all currents flow in the *z*-direction with a uniform distribution of the current density over the cross-section area. The output signals from the FEM model consist of the induced currents in the sensor elements. These currents are in the form of complex-valued phasor notation. Together these currents constitute a $N\times 1$ signal vector, here denoted as $\mathbf{e} = [e_1\ e_2\ e_3 \cdots e_N]^{\mathrm{T}}$. This signal vector **e** is used as an error signal for estimation of the *M* actuator signals.

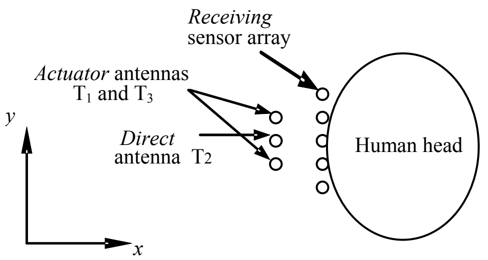

Fig. 1. A simple 2D-model of the antenna array system with 2 actuator antennas and 5 sensor antennas.

The physical system described by the FEM model above can be described as a MIMO (Multiple Input Multiple Output) system. The system described by the FEM model in Fig. 1 consists of three transmitting antennas and five receiving antennas as shown in Fig. 2. The centre antenna T_2 is transmitting the signal that we want to cancel (it acts as the antenna on any ordinary mobile telephone) and the two flanking transmitting antennas (T_1, T_3) are denoted as actuator antennas. The actuator antennas will be used to cancel the signal from the antenna T_2 at some specified volume in space. Each of the receiving antennas will receive the sum of the three transmitted signals.

Assuming that the system is linear, the principle of superposition can then be used to divide the MIMO FEM-model into separate parameters which describe the frequency response function between each of the transmitting antennas and the receiving antennas. Since the FEM-model has been verified experimentally to be linear and since this is a weak-stationary problem with time-harmonic signals, it is sufficient to describe the frequency response functions as complex-valued numbers. These complex-valued numbers describe the change in amplitude and phase due to the distance between the different combinations of transmitting and receiving antennas. Therefore the system can be described as an $N\times M$ complex-valued matrix

$$\mathbf{H} = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) & \cdots & H_{1M}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) & \cdots & H_{2M}(\omega) \\ H_{31}(\omega) & H_{32}(\omega) & \cdots & H_{3M}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ H_{N1}(\omega) & H_{N2}(\omega) & \cdots & H_{NM}(\omega) \end{bmatrix}. \qquad (1)$$

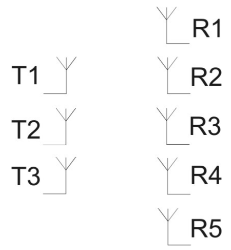

Fig. 2. The MIMO antenna array system. In this figure, a MIMO system with 3 transmitting and 5 receiving antenna elements is used. Later, different sizes and element spacing will be investigated.

3. The Least Mean Squares Solution

To get the best possible attenuation in energy sense at the receiving antenna array ($R_1 \cdots R_5$ in Fig. 2), the total energy output ξ of the error signal **e** at the receiving antennas must be as low as possible. One approach to achieve this task is by incorporating a complex valued filter **w** to control the actuator-signals, so that the actuator-signal is an amplitude- and phase-shifted copy of the input signal. This would allow control over the signals going to the actuator antennas. If it is assumed that **w** is linear and the noise is additive and Gaussian (AWGN) which is superimposed on the received signal, then the minimum residual mean energy of the error signal can be expressed as

$$\xi_{\min}(\mathbf{w}) = \min_{\mathbf{w}} \xi = \min_{w} \mathrm{E}\{|\,\mathbf{e}\,|^2\}. \qquad (2)$$

The minimum point $\xi_{\min}$ is obtained with the complex filter weight solution $\mathbf{w}_{\mathrm{opt}}$ as shown in previous work [5]

$$\mathbf{w}_{\mathrm{opt}} = -\mathbf{R}_{\mathrm{F}}^{-1}\mathbf{p} \qquad (3)$$

where **p** represents the crosscovariance between the *direct* channel (the signal from the direct antenna T_2) and the *forward* channels (actuator signals) and $\mathbf{R}_{\mathrm{F}}$ is the covariance of the *forward* channels.

The optimal **w** calculated in equation (3) can now be used to control the signals in the actuator antennas. By solving the FEM-model the resulting power density magnitude can be plotted and evaluated as shown in Fig. 3. To find these optimal filter weights we have in previous work

[4, 5] tested several adaptive algorithms and of which two Filtered-X adaptive algorithms: the Normalized LMS (NLMS) [1, 2] and the Actuator Individual NLMS [3] were found to be working well in this application. These algorithms were chosen because of their ability to handle non-stationary signals, and they provided the best compromise between complexity and performance.

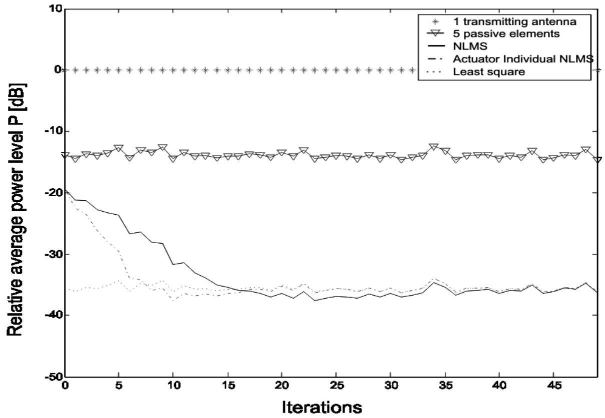

Fig. 3 The average power level inside the human head relative to the power level of a single transmitting antenna. The top graph shows the result of using only one transmitting antenna and no receiving antennas, and is used as a reference for the other methods. These results were obtained using N=5 sensor elements and M=2 actuator elements.

4. Simulation Results

The Least Mean Square solution obtained above is the optimal solution in energy sense for this problem. This particular solution (Fig. 3) is only valid assuming the position of each element does not change. However, there might be positions of the antenna elements that are more favorable with respect to the power density inside the head. By changing the spacing of the antenna elements during calculations of the attenuated power level inside the human head we will investigate if there exist some optimal spacing between the different antenna elements.

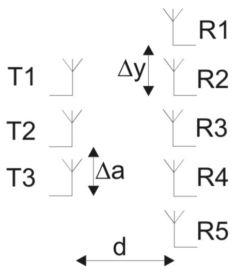

Fig. 4. The MIMO system showing the three variables of the antenna displacement.

In this FEMLAB model setup we assume three degrees of freedom (DOF), as shown in Fig. 4: the spacing between the sensor elements, denoted Δy, the distance d between the sensor element array (the receiving elements) and the actuator element array (the transmitting elements), and the spacing between the actuator elements, denoted Δa.

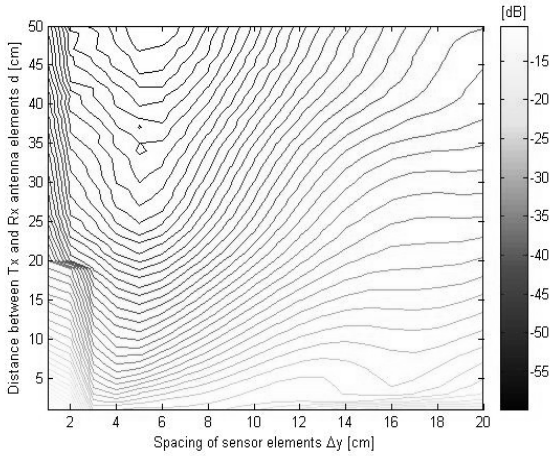

Fig. 5. The power level inside the head as a 2D cost function $J(\Delta y,d)$ with respect to the spacing between the sensor elements and the distance between the transmitter- and receiver antennas. These power levels refer to a system with N=5 sensor elements and M=2 actuator elements.

We start by investigating the effects of spacing of the sensor elements and the distance between the transmitter and receiver antennas on the power level inside the head (see Fig. 5). It is clear from this figure that the farther apart the transmitter and receiver antennas are positioned the lower the power level is inside the head. This is due to the increase of the distance d (see Fig. 4) between the transmitting and receiving antennas. Increasing this distance will also lead to an increase of the distance between the transmitting antennas and the head which will decrease the power level inside the head.

By further analyzing Fig. 5 we can see that the two-dimensional cost function $J(\Delta y,d)$ is flattening out at a distance d of approximately 25 cm. The spacing between the sensor elements (receiving elements) at the distance d=25 cm should be approximately 5 cm. With this spacing the sensor element array will cover a larger portion of the head. By using these values as a good approximation of the optimal displacement of the actuator elements and the distance between the sensor elements this would result in an attenuation of approximately 50-55 dB's. Using these values as a starting point, Fig. 6 shows how the separation of the actuator antenna elements Δa affects the power level of the cost function $J(\Delta y,d)$ inside the head.

From Fig. 6 we can see that the attenuation inside the head will increase as the spacing between the actuator elements decrease. This is a consequence of the electromagnetic waves being transmitted from almost the same point in space. The theoretical extreme of this is to place all actuator antennas in the exact same position, which will give a complete cancellation of the waves and would give a zero power level inside the head.

According to this analysis we need a MIMO antenna system that has a spacing of 5 cm between the sensor elements and a spacing of 3 cm between the actuator elements. The distance between the sensor elements and actuator elements should be about 25 cm or more. This would result in a MIMO antenna system with a size of approximately 25 by 20 cm which is not practical to place on top of a mobile phone. However, we foresee other applications where this size would be practical. Studying Fig. 5 we observe that if the original positions of the antenna elements, with an actuator antenna spacing of 2 cm is used and increase the spacing of the sensor elements from 2 cm to 3 cm this would give an extra 3 dB's attenuation inside the head.

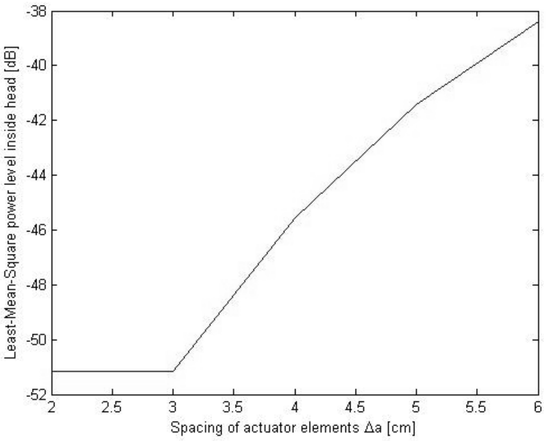

Fig. 6. The effect of increasing the spacing Δa between the actuator antenna elements. This figure was calculated with a sensor array spacing of Δy=5 cm and a separation between the sensor array and the actuator array of d=25 cm.

We have also investigated the effect on the performance resulted from changing the number of antenna elements in the actuator and sensor arrays. In this simulation we have calculated the least mean square solution as a function of the number of antenna elements in the actuator array M and the sensor array N. Fig. 7 shows, as expected, a decrease in the power level inside the head as long as every new added sensor element cover more of the head. Although, when the sensor array extends outside the length of the human head we attain no further improvement in the attenuation. Another interesting observation from Fig. 8 is that if the number of actuator elements is larger than the number of sensor elements the system becomes unstable.

Finally, another factor that is of interest is the carrier frequency of the system. The suppression of the electromagnetic field inside the head has so far been analyzed at the GSM frequency band centered at 900 MHz. Thus, we investigate the effect of using this system at other carrier frequencies and evaluate its performance at UMTS and other GSM frequency band. In this simulation we sweep the carrier frequency of the system between 500 MHz and 2.5 GHz and the results are presented in Fig. 8. It is evident from this figure that we have a minimum point at the carrier frequency of 950 MHz. This optimum frequency is dependent on the type and size of the different antenna elements. It can also be noted from Fig. 8 that the attenuation of the power level at GSM/UMTS frequencies does not differ by more than 3-4 dB's.

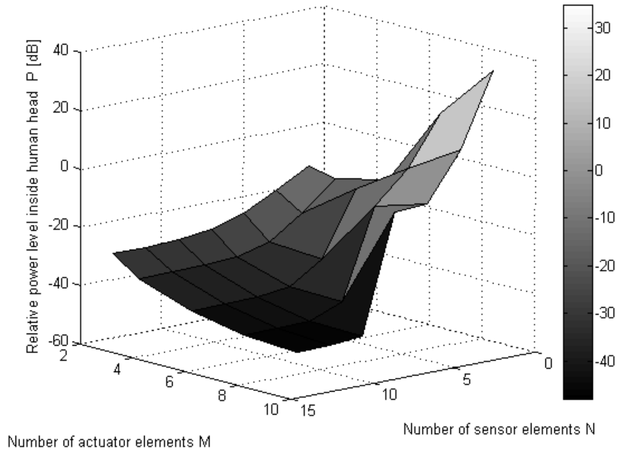

Fig. 7. The relative power level in dB's as a function of the number of elements in the actuator and sensor array.

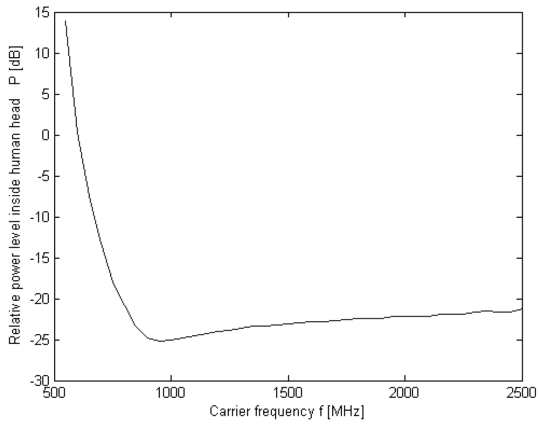

Fig. 8. The change in power levels inside the human head at different carrier frequencies. This simulation was done with a sensor array spacing of Δy=3 cm and a distance between the sensor array and the actuator array of d=3 cm.

5. Conclusions

In this paper we have presented active control algorithms combined with a MIMO system for the purpose of suppressing the electromagnetic field at a certain volume in space. In addition, we have investigated the effects of the size and number of MIMO antenna elements on the performance of the system and also tested the algorithms at different carrier frequencies. In future work it would be interesting to extend this work into a 3D model and to calculate the SAR value and the temperature increase in the brain tissue.

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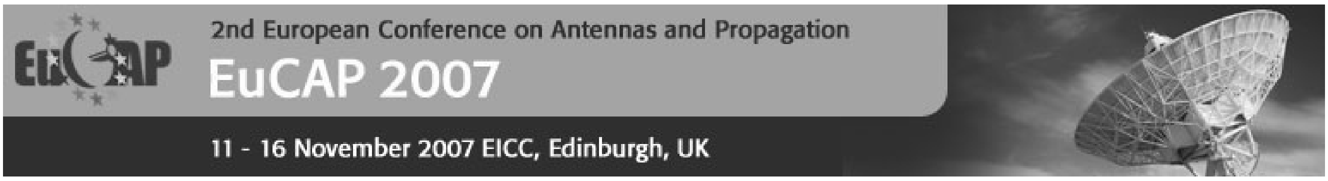

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