Directional In-Quadrature Orthogonal-Coil Antenna and an Array Thereof for Localization Purposes within a Human Body in the Fresnel Region. Numerical Simulations

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Abstract—In-body localization implies identifying 3D positions of thermometer pills, smart pills, and other autonomous small objects within the human body. The use of far-field scanning arrays operating at frequencies above 900 MHz is generally prohibitive due to severe multipath caused by different electric properties of body organs. On the other hand, the magnetic properties of the body are constant. Therefore, the standard method is that of (quasi) magnetostatics. An intermediate region between the two extremes is the Fresnel region, which approximately corresponds to the center frequency of 400 MHz and the wavelength of ~10 cm within the body. In this study, we describe the new concept of a directional receiving antenna array intended for localization purposes within a human body in the Fresnel region. The individual array element is composed of two small orthogonal coils (magnetic dipoles). The coils are to be acquired/driven in quadrature, for both CW and pulse signals. The individual array element possesses a highly-directional single-lobe beam into the body directed at 45 degrees from the broadside. An array of such radiators makes it possible to develop a simple yet effective localization algorithm within a realistic body using direct RSS estimates for every individual receiver.

Index Terms—Antenna arrays, Beam steering, Biomedical communication, Biomedical electromagnetic imaging

I. INTRODUCTION

IN-BODY localization implies identifying 3D positions of thermometer pills, smart pills, and other autonomous small objects within the human body. The use of far-field scanning arrays operating at frequencies above 900 MHz is generally prohibitive due to severe multipath caused by different permittivities and electric conductivities of body organs, skin, muscles, and fat. On the other hand, the permeability and the magnetic loss tangent of the body are constant. Therefore, the standard method is that of (quasi) magnetostatics where the direction of the imposed 3D magnetic field is acquired by a sensor, which results in encoding the sensor location. Commercial magnetic surgical navigation systems include the Medtronic Axiem, Northern Digital's Aurora, Ascension Technology (Flock of birds, microBird), Biosense Webster, Calypso, Polhemus, Praxim's Surgetics, GE Medical, etc. The magnetostatic systems are bulky and hardly wearable; the sensor must be cable- or battery-powered.

An intermediate region between the two extremes is the Fresnel region, or the radiating near field, which approximately corresponds to the center frequency of 400 MHz and the wavelength of ~10 cm within the body. In this study, we describe the new concept of a directional receiving antenna array intended for localization purposes of a small radiating source within a human body in the Fresnel region.

A. Magnetic (electric) dipoles on the air-dielectric interface in the quasi-static limit

In the quasi-static limit, an extensive study of magnetic dipoles (electrically small loop/coil antennas) radiating into or immersed within a lossy dielectric has been performed by J. Wait and co-workers [1]-[4] and A. Baños [5]. The quasistatic limit implies that the conduction current in a lossy medium dominates the displacement current, i.e.

\[ \sigma \gg \varepsilon \omega \]  \hspace{1cm} (1)

where \( \sigma \) is the medium conductivity, \( \varepsilon \) is the dielectric constant, and \( \omega \) is the angular frequency. No significant directive properties of magnetic (and electric) dipoles radiating close to an air-dielectric interface have been established [5]. Average human body properties might be characterized by \( \sigma = 0.5 \text{ S/m} \), \( \varepsilon = 30 \varepsilon_0 \), Eq. (1) is then satisfied (assuming \( \sigma > 10 \omega \varepsilon \)) only at frequencies below approximately 20 MHz.

B. Magnetic (electric) dipoles on the air-dielectric interface in the far field

Using a 2D spatial Fourier transform to solve Maxwell’s
equations, G. Smith [6] established radiation patterns for horizontal magnetic(electric) dipoles at the air-dielectric interface. He found that the horizontal dipoles may create highly-directive patterns into a dielectric, with off-broadside main lobes. This effect occurs when the dipole is close to the interface and when the dielectric contrast of two media is reasonably large \((\varepsilon_r, \varepsilon_s = 4)\). This effect is weakly influenced by conductivity of the medium. Using a similar approach, W. Lukosz and R. E. Kunz [7], [8] have derived analytical radiation patterns for vertical magnetic(electric) dipoles, and arrived at a similar conclusion. Electric dipole patterns were investigated in [9] and [10] (including finite wire dipoles). Results for finite (resonant) loops are given in [11] and [12]. Near-field electric-dipole radiation dynamics through Finite Difference Time Domain (FDTD) modeling have been quantified in [13].

C. Frequency band under study

We will consider wideband pulse propagation with a center frequency of around 400 MHz, which is within the UHF band. Thus, the pulse spectrum will include a band newly established by the FCC Medical Device Radiocommunication Service used for diagnostic and therapeutic purposes in humans at 401-406 MHz. If average human body properties of \(\sigma = 0.55 S/m, \varepsilon = 50 \varepsilon_s\) are used, the fields within the human body medium at 400 MHz do not exactly correspond to the far field. Instead, the bulk of the body volume in any direction belongs to the Fresnel region of operation (the radiating near field). Nevertheless, some general facts established with the help of the far-field models [6], [8], [12] will be quite helpful in providing theoretical background of our model.

D. Model of orthogonal magnetic dipoles

In order to create a highly-directive one-lobe beam into the body medium in the Fresnel region, we suggest using two orthogonal magnetic dipoles (small coil antennas) with coincident phase centers. The problem geometry is shown in Fig. 1. The upper half-space is free space while the lower half-space is a dielectric. Both dipoles have the same magnetic moment, \(m\); they are oriented as shown in Fig. 1.

II. PATTERN COMBINATION OF TWO ORTHOGONAL DIPLOES IN THE FAR FIELD

A. CW radiation patterns in a lossless medium

With reference to Fig. 1, the radiated far-field electric-field component \(E_{x_\theta}\) of the horizontal magnetic dipole in a lossless medium has the form

\[
E_{x_\theta}(\theta, \phi) = \sum_{nm} \alpha_{nm} \exp\left[\frac{j \varepsilon_{nr} \sin \theta}{\varepsilon_{nr} \sin \theta} \left( -jk \sqrt{1 - n^2} \sin \theta \right) \right] \left( \frac{2 \sin \phi \sin \theta}{\sin \phi \sin \theta} \right)^{\frac{1}{2}} \left( \frac{\sin \phi}{\sin \phi} \right)^{\frac{1}{2}} \left( \frac{\cos \phi}{\cos \phi} \right)^{\frac{1}{2}} \exp\left[\frac{j \varepsilon_{nr} \sin \theta}{\varepsilon_{nr} \sin \theta} \left( -jk \sqrt{1 - n^2} \sin \theta \right) \right] \tag{2a}
\]

Here, \(n = \sqrt{\varepsilon_r/\varepsilon_s}\) is the relative refractive index, \(k_{ls} = m/\varepsilon_{ls}\), and \(m\) is the magnetic dipole moment. Equation (2a) follows from (Eq. 2b) and (Eq. 47d) of Ref. [6]. When \(n = 1\), it is reduced to the isolated magnetic-dipole pattern in the lower half-space (\(\cos \theta = \cos \theta\)).
C. CW radiation patterns in a lossless medium

The key observation is that Eqs. (3a) and (3b) become identical to within: (i) a phase factor of \( \exp(j \pi / 2) \) corresponding to a quadrature phase delay between two dipoles of the quarter wave period, \( \tau_q \), in free space 1 and (ii) a space factor, \( \text{sign}(y) \). This space factor obviously indicates that the two main lobes of the vertical dipole are out of phase.

Therefore, two orthogonal magnetic dipoles in quadrature should produce a highly directional beam with only one main lobe: either along \( \theta = 45^\circ \) and \( \phi = 90^\circ \) (y > 0) or along \( \theta = 45^\circ \) and \( \phi = 270^\circ \) (y < 0), while exactly cancelling out the other lobe. This concept is shown in Fig. 2 where the radiation pattern into lower half space is depicted. The dashed curve is the normalized linear pattern, \( |E_\theta| \), of either (horizontal or vertical) dipole from Eqs. (3). The solid curve is the pattern combination from Eqs. (3) when the horizontal dipole has a time delay, \( t \rightarrow t - \tau / 4 \). Equations (3) predict a perfect cancellation of one lobe and a creation of a highly-directive beam into the dielectric at 45 degrees from broadside. In order to re-direct the main beam into the third quadrant, either the horizontal dipole should be subject to a negative time delay \( t \rightarrow t + \tau / 4 \) or the vertical dipole should obey a positive time delay, \( t \rightarrow t - \tau / 4 \).

III. PATTERN COMBINATION OF TWO ORTHOGONAL DIPOLES IN THE FRESNEL REGION

A. Wideband pulse signal

We intend to show that the theoretical prediction of the previous sections also holds in a Fresnel zone within a (highly lossy) human body for wideband pulses with the center frequency of 400 MHz. In this and following sections, a bipolar Gaussian (Rayleigh) excitation current pulse is used for a TX antenna in the form

\[
i(t) = I_0 \left( t_{\theta_0} - t \right) \exp \left( \frac{-(t - t_{\theta_0})^2}{2\tau^2} \right), \quad t_{\theta_0} = 5\tau, \quad I_0 = 1A
\]

Its center frequency and a 3dB-power bandwidth are given by

\[
f_c = \frac{0.16}{\tau}
\]

\[
\text{BW} = 1.15 f_c
\]

We employ \( \tau = 0.4\mu s \Rightarrow f_c = 400 \text{ MHz}, \quad \text{BW} = 460\text{MHz} \) in all examples given in the following text. Other pulse forms have been checked with similar results. The in-quadrature CW condition may be transformed to the pulse delay of \( \sqrt{2}\tau \) to achieve the proper phase synchronization for two pulses. This pulse delay is within 10% of the expected time delay of one quarter wave period for a CW signal with frequency, \( f_c \).

B. Numerical simulations and their results

Numerical simulations are carried out using the standard 3D FDTD method (cubic Yee cells with cell size, D, of 5mm or 2.5mm) for antennas just above a dielectric brick with the average properties of the human body given as \( \sigma = 0.55\text{S/m}, \quad \varepsilon = 50\varepsilon_o \). An accurate source model with coincident phase centers has been employed [15]-[17]. Three examples (individual horizontal TX magnetic dipole, individual vertical TX magnetic dipole, orthogonal-coil radiator) have been considered with parameters from Table 1. The corresponding geometry including the H-field probes is shown in Fig. 3. Figure 4 shows the snapshots of the radiated electric field, \( E_z \). To the right, sampled magnetic fields at probe locations are plotted. Figure 4 demonstrates that the beamforming effect clearly takes place.

Table 2 quantifies the beamforming effect from Fig. 4. The table is obtained on the base of three examples reported above. The array of two orthogonal coils with the time delay performs almost ideal signal addition in the desired direction (0.73A/m versus the ideal result of 0.8A/m). The signal in the undesired direction is about 18 dB weaker than the main signal (powerwise). Similar results have been observed for harmonic excitation. Table 2 may be rewritten in terms of the radiating E-field, \( E_y \), too.

![Fig. 2. Normalized dipole radiation patterns into the lower half-space. The dashed curve is the normalized linear pattern, \( |E_\phi| \), of either (horizontal or vertical) dipole from Eqs. (3). The solid curve is the pattern combination from Eqs. (3) when the horizontal dipole has a time delay, \( t \rightarrow t - \tau / 4 \). Arrows indicate magnetic field directions.](image)

![Fig. 3. Geometry assembly for individual coils and for the orthogonal-coil quadrupole antenna](image)
IV. CONCEPT OF A RECEIVING ARRAY OF WIDEBAND ORTHOGONAL-COIL ANTENNAS ON A HUMAN BODY SURFACE

A. Array concept – RSS array

The concept of a scanning receiving array utilizes pattern reciprocity; it is shown in Fig. 5. The dark circle represents a transmitting antenna within the body (e.g., a “smart pill”). With a positive set of time delays, the maximum RSS will be received by antenna #3. If a negative set of time delays is used, the maximum RSS signal will be received by antenna #1. A simple triangulation allows us to find the TX target location in the yz-plane. A similar concept applies to 2D scanning.

The array in Fig. 5 is not the phased far-field array in the classical sense: we do not really combine the received voltages from individual radiators with different phase shifts. Instead, we estimate the RSS for every individual radiator and make a decision based on this data. This circumstance might enable a great stability of results with respect to significant random variations of the human-body dielectric medium. The operating volume of the array is restricted to the Fresnel region; it is on the order of the array size. Large circles in Fig. 5 represent a “safe” detection region (region 1) whereas the small circles correspond to a “conditional” detection (region 2).

B. Proof of array concept using numerical simulations for a body phantom

Emphasize that, irrespective of a possible rotation of any two-coil combination in Fig. 5 about its axis of symmetry, the main beam will always be directed at 45 degrees from the vertical axis into the dielectric material. This remarkable property follows from the expansion of any quadrupole into two axes-aligned dipoles; it was verified numerically.

Figure 5 shows how the four-element array from Fig. 5 is applied to a localization problem within a human body phantom. A custom torso phantom manufactured by The Phantom Laboratory, NY was scanned using a Model WB4
whole body color scanner manufactured by Cyberware, Inc., CA. A transmitting coil antenna to be localized is located inside the body, at a 100mm normal distance from the back – see Fig. 6a. Its position corresponds to a movement through the oesophagus. Received open-circuit voltages are recorded for every orthogonal-coil receiver. The receiver separation distance is 80mm. The Rayleigh pulse described by Eqs. (4) is used.

In Fig. 6a, the homogeneous phantom medium with
\[ \sigma = 0.5 \text{S/m, } \varepsilon = 50 \varepsilon_0, \]
was used for the simulations. In Fig. 6b, an artificial composition of generic human body organs within the phantom has been created using appropriately scaled and positioned organs and bones (over 47 individual manifolds). The dielectric properties of organs at 400MHz have been acquired from [19], [20]. Furthermore, using a Constructive Volume Geometry (CVG) algorithm, we created two layers of uniform normal thickness on the body surface: a 2mm thick skin layer (\( \sigma = 0.75 \text{S/m, } \varepsilon = 47 \varepsilon_0 \)), and a 6mm thick fat layer (\( \sigma = 0.18 \text{S/m, } \varepsilon = 12 \varepsilon_0 \)).

To the right of Fig. 6a and Fig. 6b, the received voltages for every orthogonal-coil antenna are given, after direct or reverse in-quadrature combination, respectively. Note that every coil pair is rotated by 45 degrees in Fig.6. According to Fig. 6, the array operates as expected for either phantom: the positive set of time delays gives the maximum RSS at antenna #3 of the array whereas the negative set of time delays gives the maximum RSS at antenna #1. This is exactly the scheme of Fig. 5.

Note that the array functions despite a rather sophisticated environment in Fig. 6b. This is a critical observation from the viewpoint of practical applications. Table 3 gives the L2-norm for every received pulse in both cases. The multipath effect decreases the pulse strength at antenna #1 for the negative set of time delays as compared to the homogeneous solution.

C. Superior performance of the orthogonal-coil array compared to an ordinary array

Figure 7 replaces the array of orthogonal-coil antennas in Fig. 6 by an array of ordinary coil antennas (conventional magnetic dipoles) with the same polarization as the original source. All other problem parameters remain the same. One can see that the RSS test barely points toward the closest array element (#2) given the complicated body shape and composition. Thus, the orthogonal-coil array quite significantly outperforms the ordinary receiving array.

V. DISCUSSION AND CONCLUSIONS

We described and justified, both theoretically and numerically, the new concept of a small directional receiving antenna array intended for localization purposes within a human body in the Fresnel region. The array element is composed of two small orthogonal coils (magnetic dipoles). These coils are to be driven/acquired in quadrature, for both CW and pulse signals. An array of such radiators makes it possible to develop a simple yet effective localization algorithm within the body using RSS (Received Signal Strength) estimates for every individual radiator.

The observed array performance in a complicated dielectric environment is explained as follows. To a certain degree, the array still utilizes near-field behavior of magnetic antennas, which is weakly affected by variable dielectric properties. On the other hand, every individual orthogonal-coil antenna forms a directional beam already in the Fresnel region, which significantly improves RSS estimates as compared to ordinary coil antennas (magnetic dipoles). Numerical simulations have shown that the directional beam is formed at distances greater than quarter wavelength in the body (~2.5cm at 400MHz) from the orthogonal-coil radiator.

![Figure 6](image_url)

**TABLE III**

<table>
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<tr>
<th>Phase</th>
<th>Body Type</th>
<th>Receiver #1</th>
<th>Receiver #2</th>
<th>Receiver #3</th>
<th>Receiver #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Homogeneous</td>
<td>6.9×10^4</td>
<td>2.2×10^4</td>
<td>7.8×10^4</td>
<td>2.7×10^4</td>
</tr>
<tr>
<td>Negative</td>
<td>Homogeneous</td>
<td>8.6×10^4</td>
<td>1.4×10^4</td>
<td>8.7×10^4</td>
<td>2.7×10^4</td>
</tr>
<tr>
<td>Positive</td>
<td>Inhomogeneous</td>
<td>2.6×10^4</td>
<td>1.4×10^4</td>
<td>8.0×10^4</td>
<td>5.1×10^4</td>
</tr>
<tr>
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<td>Inhomogeneous</td>
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<td>2.3×10^3</td>
<td>7.1×10^4</td>
<td>3.1×10^6</td>
</tr>
</tbody>
</table>
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Draper Laboratory coils have the moment circuit voltages. The in

Fig. 7. Left – RX array of orthogonal-coil antennas; right – received open-circuit voltages. The in-body TX coil has the magnetic moment $\pi \times 10^{-9}$ Am$^{-1}$; array coils have the moment $\pi \times 10^{-10}$ Am$^{-1}$.

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REFERENCES


