Miniaturized antennas for link between binaural hearing aids

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Miniaturized Antennas For Link Between Binaural Hearing Aids

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***Abstract*— We have investigated the possibility of using the 2.45 GHz ISM band for communication between binaural hearing aids. The small size of a modern hearing aid makes it necessary to miniaturize the antennas to make this feasible. Two different types of hearing aid placements have been investigated: in the outer ear and in the ear canal. Both put strict demands on the size of the antenna, which have been miniaturized by applying disc loads and high permittivity materials. The investigations have been done by FDTD simulation of a modified SAM phantom head, where we have included a simple model of the ear canal. Simulations show that the outer ear placement is better, as it gives a total link loss of 48 dB. The placement in the ear canal gives a total link loss of 92 dB.**

I. INTRODUCTION

Binaural processing in audiology is the capability of the brain to process sound coming from both the left and the right ears which helps in localizing the source of a sound [1]. Modern binaural hearing aids use adaptive filtering for noise suppression. Synchronization of such hearing aids is important for improved hearing in noisy environments. Unsynchronized hearing aids may result in loss of localization and thus the user may not be able to predict the direction to the source of the sound correctly. Size and power are the two main challenges for designing a system which could be embedded into hearing aids for communication with each other. One alternative is to use Near Field Magnetic Induction (NFMI) for transmission of information as used in Oticon Epoq [2].They communicate binaurally with a built-in radio transmitter using NFMI technology at 3.84 MHz[3]. Design of a low power wireless hearing aid communication system using packaged antenna for behind-the-ear (BTE) placement at 400 MHz has been discussed in [4]-[5].

This paper explores the possibility of using 2.45 GHz ISM band for establishing wireless communication link between hearing aids using small antennas. The two main challenges in implementing this are the size of the antenna and the presence of the human head, which is a lossy medium for electromagnetic wave propagation. Miniaturization of a monopole antenna is achieved by embedding them into a dielectric of high permittivity and loading them with a disc [6]. Two positions has been explored, (a) by inserting the antenna into the ear canal and (b) by using the antenna outside the ear. These two positions can be used for into-the-canal (ITC) hearing aids and into-the-ear (ITE) hearing aids respectively. Disc loaded monopole antennas embedded inside high permittivity material were simulated for both the ITE and ITC scenarios. All simulations were done in commercially available SEMCAD [13] which uses the FDTD method.

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II. NUMERICAL HEAD MODEL

Many numerical head models have been used in the literature [7]-[10]. They have typically been used either for simulating an implant antenna or for measuring radiation effects from the mobile phones. These models do not have ear canals. The ear canal is basically an air filled tube and has significant effect on the antennas in the hearing aids. The SAM phantom model provided by SEMCAD [13] has been modified to include ear canals. The ear canal has been modeled as a cylindrical air cavity having a diameter of 7mm and a length of 26mm, which is a realistic model for average adult human ear canal [11]. Homogeneous electrical property of human head (dielectric constant, ε_r = 39.2 and conductivity, σ_e = 1.80 S/m) at 2.45 GHz is considered for the SAM liquid. These electrical properties are that of equivalent head tissue given in [12]. The SAM shell was assumed to have ε_r = 3.7. Fig. 1 shows the dimensions of the model. A homogeneous head model was used in order to reduce the simulation time and to get results which are independent from the variation between the different available heterogeneous head models.

III. WAVE PROPAGATION THEORY

A. Wave Propagation inside Head

Classical theory deals with antennas placed inside a lossless medium. But for scenarios like ITC, the antenna no longer remain inside a lossless medium, rather it is inside a lossy medium characterized by the electrical properties of the surrounding which in this case is the head tissue [14]. The complex permittivity of a medium, ε_c is defined as:

$$\varepsilon_c = \varepsilon_e - j\frac{\sigma_e}{\omega} \quad (1)$$

where σ_e is conductivity and $\omega = 2\pi f$, f being the frequency.

The permittivity ε_e is scaled with the permittivity of vacuum ε_0 = 8.854×10^{-12} as $\varepsilon_r = \frac{\varepsilon_e}{\varepsilon_0}$. The complex wavenumber of a lossy medium is defined as:

$$k = \omega\sqrt{\mu\varepsilon_c} = \omega\sqrt{\mu(\varepsilon_e - j\frac{\sigma_e}{\omega})} = \omega\sqrt{\mu(\varepsilon_r\varepsilon_0 - j\frac{\sigma_e}{\omega})} \quad (2)$$

For radiation from an antenna in a lossy medium, two separate loss mechanisms contributes: (a) Attenuation loss, proportional to $e^{-2\alpha R}$, where $\alpha = |Im[k]|$ and (b) dissipation

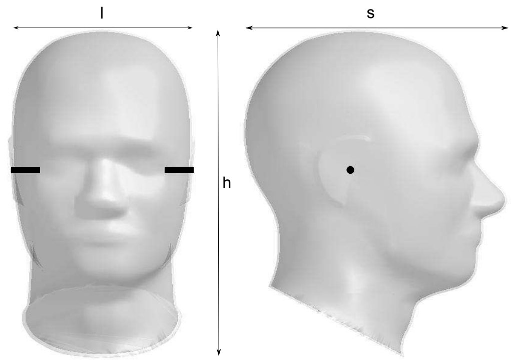

Fig. 1. Modified SAM phantom model with ear canals with l=164mm, h=312mm, s=234mm. Left:Front View, Right:Side View. The cylindrical ear canals are drawn in black. Its radius is 3.5mm and the length is equal to 26mm.

loss in the reactive energy stored in the near field around the antenna [15].

From the extended Friis formula for a lossy medium [15], path loss in a lossy medium can be written as:

$$(PL)_{lossy\_medium} = \left(\frac{\lambda_{eff}}{4\pi R} e^{-\alpha R} \right)^2 \quad (3)$$

where $\lambda_{eff} = \frac{2\pi}{Re[k]}$ is the effective wavelength in a lossy medium and R is the distance between the transmitting and receiving antennas.

B. Wave propagating around the head

A creeping wave is the phenomenon by which the receiving antenna located on the other side of a head receives the signal. This phenomenon is common for on body surface propagation [16]. A creeping wave can be modeled as a free space wave with some extra loss because of the creeping phenomenon, with a distance traveled, same as that of the curvature of the head and with a loss exponent $n > 2$, because no direct line of sight exist. This scenario is applicable for the ITE hearing aids.

IV. ANTENNA DESIGN

A. Size reduction Technique

Two methods for the size reduction of the monopole antenna have been tested. The first one is loading the monopole antenna with a disc. Further size reduction has been achieved by embedding it in a dielectric medium [17]. For a dielectric medium of infinite extent, the size reduction factor, F_r is equal to $\sqrt{\varepsilon_r}$ of the medium. In a practical antenna for hearing aids, the size reduction factor, F_{ra} will be a function of the shape, size, electrical characteristics of the dielectric material, electrical properties of the head tissues and the position of the antenna with $F_{ra} < F_r$.

B. Antenna Structure

The antennas were optimized for the return loss, $S_{11} \leq -10$ dB and the bandwidth in 2.45 GHz ISM band. The degrees of freedom which could be optimized are dimensions and the dielectric constant of the dielectric, the radius of the ground plane, the length and the radius of the central conductor and the radius of the disc load. For ITE antenna, the dimensions of the dielectric was chosen such that it fits inside the outer ear and that for ITC was chosen so that it fits inside the ear canal. The radius of the disc load (r_{disc}) and the central conductor (r_{mp}) was fixed to reduce the degrees of freedom. The length of the central conductor (l_{mp}), the radius of the ground plane (r_g) and the dielectric constant were varied to get a minimal return loss in 2.45 GHz ISM band. Table I summarizes the optimized antennas dimensions and the dielectric constant of the material needed to embed them. The dielectric material has been assumed to be lossless ($\sigma_e = 0$). It should be noted here that other values may also result in the optimized values for the return loss and the bandwidth depending upon which degree of freedom is kept constant.

1) ITE Antenna: For the ITE antenna, disc loaded monopole was embedded in a cylindrical dielectric of $\varepsilon_r = 56$ of the radius, $r_{d\_top} = 10mm$ and the height, $l_{d\_top} = 11mm$. The ground plane was at a distance, $d = 1.75mm$ from the bottom of this dielectric element. However, an additional cylindrical dielectric element was required below this top cylindrical dielectric element for impedance matching with same ε_r of the radius, $r_{d\_lower} = 3.5mm$ and the height, $l_{d\_lower} = 8.5mm$ because of the ear canal and the presence of the human head. The axis of these dielectric elements coincides with the axis of the disc loaded monopole. Fig. 2 illustrates the geometry of the ITE antenna.

2) ITC Antenna: For the ITC antenna, the disc loaded monopole was embedded into a cylindrical dielectric ($\varepsilon_r = 49$) material of the radius, $r_d = 3.5mm$ and the length, $l_d = 11mm$ at the center of the dielectric element with the axis of the disc loaded monopole perpendicular to that of the dielectric element. Geometry for the ITC antenna is illustrated in Fig.3.

V. SIMULATION SETUP

Fig.4 shows the model with the antennas position for the simulation. The orientation of the antennas was chosen so that the coupling between the left ear antenna and the right ear antenna was maximized. For the ITE case, the lower dielectric element was inserted into the ear canal so that the axis of antenna and the ear canal's axis are collinear. Since the monopole has broadside radiation pattern, the main part of the radiation will be in the tangential direction of the head and the electromagnetic waves will reach the other antenna by creeping along the head's surface. For the ITC case, the antenna was placed at the center of the ear canal with the axis of the central conductor vertical and perpendicular to the ear canal's axis. Simulations were done in commercially available numerical electromagnetic solver SEMCAD which uses the finite-difference-time-domain (FDTD) method. The antenna ground plane and the disc load was modeled as a thin Perfect Electric Conductor (PEC) sheet. The central monopole conductor was modeled as a thin PEC wire. A

TABLE I
ANTENNA PARAMETERS

Parameter	ITC	ITE
r_{disc}(mm)	1	1
r_{mp}(mm)	0.3	0.3
r_g(mm)	2.10	2.25
l_{mp}(mm)	5.3	4
ε_r	49	56

voltage source with an internal resistance of 50Ω was used for the antenna excitation. A Gaussian sine wave with the central frequency of 2.45 GHz and the bandwidth of 1 GHz was used for the broadband simulation. Voxelling was done with a non uniform grid setting for faster simulation [16]. An uni-anisotropic perfectly matched layer (UPML) was used as the simulation boundary around the model.

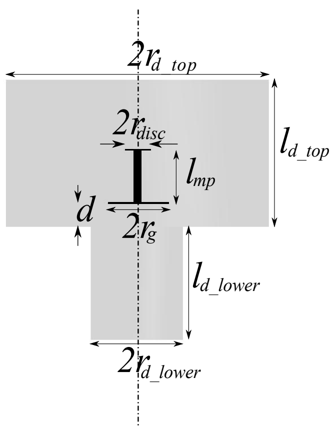

Fig. 2. Geometry for the ITE antenna. Axis of the disc loaded monopole is the same as the axis of the dielectric elements shown by dash-dotted line

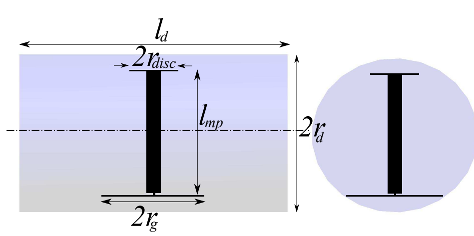

Fig. 3. Geometry for the ITC antenna. Left: front view; Right: side view. It should be noted that the axis of the dielectric element shown by dash-dotted line is perpendicular to the axis of the disc loaded monopole.

VI. SIMULATION RESULTS

A. Return Loss and Link Loss

The return loss and the antenna coupling performance is plotted in Fig.5. f_{res} is the resonance frequency and BW is the impedance bandwidth. Table II presents a summary of the simulation. If the theoretical value of the path loss is calculated from (3), we get $PL_{lossy\_medium} = -103.1$ dB for a distance, $R = 138mm$, which is the distance between the antennas for the ITC case with the $\lambda_{eff} = 19.3mm$ at

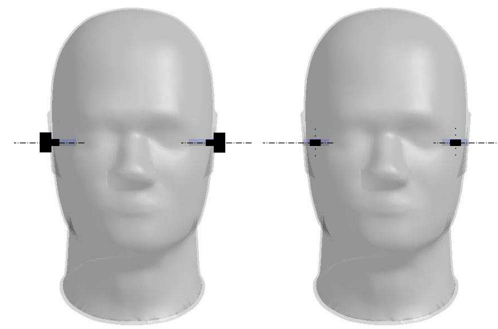

Fig. 4. Antenna placement on the models for the simulation. Left:ITE case, Right:ITC case. The dash-dotted lines shows the axis of the ear canals. In the ITC case, the axis of the central conductor is shown by the dotted lines.

TABLE II
SIMULATION RESULTS

Parameter	ITC	ITE
f_{res}(GHz)	2.46	2.44
$S11_{res}$(dB)	-11.0	-15.3
BW(MHz)	174	139.4
$S21_{peak}$(dB)	-91.7	-47.1
$S21_{2.45GHz}$(dB)	-91.7	-47.2
$S21_{res}$(dB)	-91.8	-47.1

2.45 GHz. This theory assumes an infinite lossy dielectric medium surrounding the antennas. The simulated S_{21} at 2.45 GHz has a value of -91.7 dB. The finite dimension of the head resulting in the reflections from the head-air interface contributes to the higher value of the simulated S_{21}. One more contributing factor for the higher value in the simulation is the waves that leaks out from the open end of the ear canal and reaches the receiving antenna by creeping along the head's surface as seen in Fig.6. The simulated peak value of S_{21} for the ITE case is -47.1 dB. Fig.7 shows the creeping wave phenomenon for ITE case.

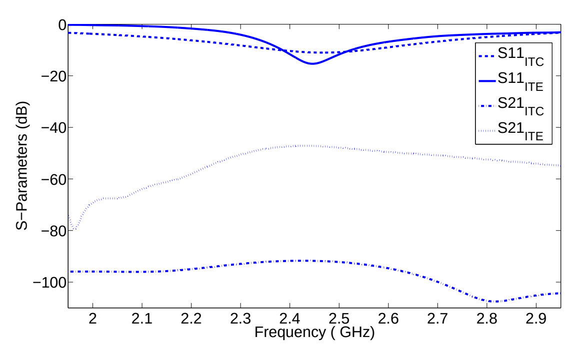

Fig. 5. Simulated return loss(S_{11}) and the coupling between the antennas (S_{21})

B. Specific Absorption Rate

Specific Absorption Rate (SAR) is the mass-normalized rate at which EM energy is absorbed by the tissue at a

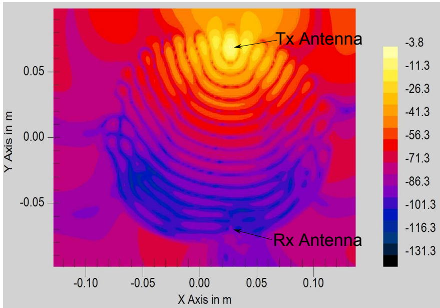

Fig. 6. Real modulus of electric field at 2.45 GHz for propagation inside head tissues sliced at the level of the antennas for the ITC case. The waves leaking out from open end of the canal can also be seen.

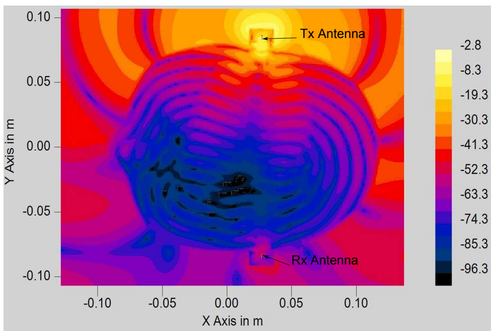

Fig. 7. Real modulus of electric field at 2.45 GHz for creeping waves as seen from top of the head sliced at the level of the antennas for ITE scenario.

specific location. SAR is an important biologically effective quantity used in protection guidelines dealing with EM energy exposure. The regulated spatial peak SAR limitation for the head in Europe is $2W/Kg$ averaged over $10g$ [18] of tissue and in USA, it is $1.6W/Kg$ averaged over $1g$ [19] of tissue. These limitations on the SAR value limits the maximum power that can be accepted by the antenna. Table III presents the maximum accepted power for the ITE and ITC antenna under these limitations. These values were calculated in SEMCAD by fast averaging IEEE-C95.3/1528 guidelines [20]-[21].

VII. Conclusions and Future Work

We have presented two antennas suitable in size and technical performance for use in establishing a wireless link between binaural hearing aids using the 2.45 GHz ISM-band. The external, ITE, case has a lower total link loss. The loss of the internal, ITC, case is higher due to the fact that the wave propagation is mainly through a lossy material.

Further analytical investigation will be done of the effects on the path loss from the internal reflections inside the head.

TABLE III
Maximum Accepted Power

SAR Limitation	ITC	ITE
$1.6W/Kg$ over $1g$	$5.5mW$	$18.4mW$
$2W/Kg$ over $10g$	$37.3mW$	$80.1mW$

Future studies will include a refined model of the middle ear and the ear canal in a heterogeneous head model as well as the upper part of the human torso, in order to get more realistic simulation results.

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