Directional Analysis of the On-Body Propagation Channels considering Human's Anatomical Variations

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ABSTRACT

This paper presents a directional analysis of the on-body propagation channels using the high resolution space alternating generalized expectation (SAGE) maximization algorithm. The analysis has been done on data obtained through FDTD simulations, on a male and a female numerical phantom. For estimating the angle of arrival (AoA) at a four element square array located at the chest, two different positions of the transmitter are considered. The presented results show that the anatomical variations between a male and a female results in different AoA for the same position of the transmitter-receiver pair. Directional analysis of the on-body channels could be used for increasing the reliability of the communication link between on-body devices.

1. INTRODUCTION

Wireless Body Area Network (WBAN) has emerged as a promising technology for providing health care and monitoring of the critical health parameters [1]-[3]. The wearable WBAN consists of on-body devices worn by the users, for example blood pressure monitors and glucose sensors. The communication between the on-body devices is mainly through the creeping waves which have exponential attenuation with the distance [4]-[6]. The directional analysis estimates the angle-of-arrival (AoA) of the on-body channels helps in determining the direction of the dominant paths on the body carrying significant energy and thus is beneficial in propagation loss estimation. Moreover, it helps in the designing of better fixed beam and pattern diversity antennas [7]. Hence, instead of having antenna radiating in all direction, the antenna beam could be steered in the direction of angle of arrivals for a better and reliable communication.

In [7], authors have estimated the angle of arrival for various on-body channels using a pattern diversity antenna. In this paper, we have presented the directional analysis of the on-body propagation channels using the high resolution space alternating generalized expectation (SAGE) maximization algorithm [8]. The angle of arrival is estimated for chest-to-back and chest-to-waist, on-body channel by the simulations on full body phantoms. A square array of four antenna elements placed at the chest is used as a receiver array and a single antenna transmitter is first placed at the back and then at the waist. Moreover, the anatomical variations between a male body and a female body affects the performance of the devices in WBAN [9]. Hence, to study the effect of the anatomical variations on the directional analysis, the investigations are done over an adult male and an adult female numerical phantoms. All simulations are done at 2.45 GHz ISM band in SEMCAD-X [10] which uses the FDTD method. The normal standing and static posture of the body is assumed. In a realistic scenario, movement of the body parts like arms, affects the on-body channels [11] and hence will also have an affect on AoA. A preliminary investigation is done with a phantom with one arm raised till shoulder level. However, details have been left for future investigations. Nevertheless, the SAGE algorithm shows the capability of estimating AoA for the on-body channels and the presented result shows that the anatomical variations between the human bodies will result in different AoA for same position of the transmitter-receiver pair.

2. METHODOLOGY

This section describes the numerical phantoms on which the simulations are done, antennas and the estimation algorithm used for the directional analysis.

2.1 Numerical Phantoms

The numerical phantoms used for the simulations are created in the 3-D CAD software POSER [12] and then imported into SEMCAD-X. They consists of a full body male and a female phantom shown in Fig. 1. The phantoms are assigned homogeneous muscle tissue electrical properties at 2.45 GHz (permittivity = 52.7 and conductivity = 1.7 S/m). Using a homogeneous phantom is a reasonable approximation at 2.45 GHz due to very low penetration depth of the electromagnetic waves and hence, the heterogeneity of the different tissues of the organs inside body will have minimal effect for the on-body propagation [13].

2.2 Antennas

The antenna used in the simulation is a disc loaded dielectric embedded compact monopole antenna (used for in-the-ear

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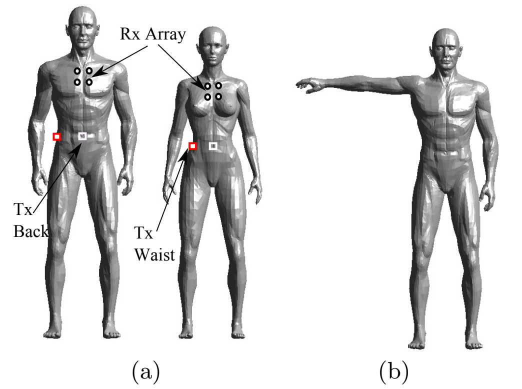

Figure 1: (a) Phantoms showing the placement of the receiver array and the transmitter position. The white square shows the transmitter position on the back side of the body. The red square shows the location of the transmitter at the waist. Each circle is an element of the receiver array. (b) Phantom with the right arm raised till shoulder level.

hearing aids), described in [14] with $S_{11} < -10$ dB in the 2.45 GHz ISM band. The antenna is perpendicularly polarized w.r.t. the body surface and has omnidirectional pattern in azimuthal plane (plane parallel to the body).

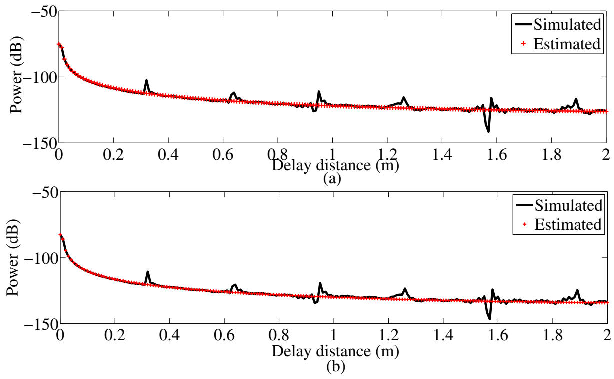

Figure 2: Simulated versus estimated impulse response using SAGE for the transmitter at the back. (a) For male phantom (b) For female phantom

2.3 AoA Estimation through SAGE

SAGE is an iterative implementation algorithm based on maximum-likelihood estimation of the parameters of the received wave. A received signal at the antenna array is modeled as sum of L multipath components (MPCs) using array steering vector and the model of the channel matrix. Each MPC is described by parameters like complex amplitude, delay and angle of arrival. A maximum likelihood function is formed using the received signal model and the observed received signal. The aim of the maximum likelihood estimation is to estimate the parameters which maximizes this function. A detail description of the application of algorithm for resolution of electromagnetic wave is described in [15]. For the simulations in this paper, we have 4 receive antenna

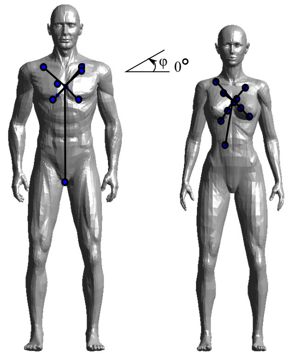

Figure 3: Estimated AoA for the transmitter antenna at the back of male and female phantom. The length of the line is proportional to the power received in the particular direction. For e.g. for the male phantom, the strongest component is received at 270° and that for the female it is at 257°

and one transmit antenna. Hence, the 4×1 channel matrix $\mathbf{H}$ can be described as sum of L plane-waves or multipath components where each wave l is characterized by a complex amplitude a_l, propagation delay τ_l and a Doppler shift ν_l [16]. For the vertical polarization (perpendicular to the body), the channel matrix at each frequency point f_k and temporal instant t_s can be modeled as:

$$\mathbf{H}(\mathbf{t_s}, \mathbf{f_k}) = \sum_{\mathbf{l=1}}^{\mathbf{L}} \mathbf{a_l} \mathrm{e}^{-\mathbf{j2\pi\tau_l f_k}} \mathrm{e}^{\mathbf{j2\pi\nu_l t_s}} \mathbf{G_{TX}}(\varphi_{\mathbf{TX,l}}) \mathbf{G_{RX}}(\varphi_{\mathbf{RX,l}}) \quad (1)$$

where $\mathbf{H} \in \mathbb{C}^{\mathbf{4\times1}}$, $\mathbf{G_{RX}}(\varphi_{\mathbf{RX,l}})$ is 4×1 complex vector representing the receiver antenna response for the elevation angle of 90° (azimuthal plane). Moreover, $\varphi_{RX,l}$ is the angle of the arrival in azimuthal plane (plane of the body). Since we are considering a static body scenario, Doppler effect is absent and hence $\nu_l = 0$ which further simplifies the case. The parameter of (1) for 10 MPCs are estimated using SAGE [8] where the observed received signal is obtained through the simulations.

2.4 Simulation Scenario

The scenarios which are considered for the AoA estimation are: (1) The receiver array at the chest and the transmitter at the back of both male and female phantom (2) The receiver array at the chest and the transmitter at the the waist for both the phantoms. The first case is a symmetrical with respect to the position of the transmitter antenna and the receiver array whereas the second is asymmetrical. They are shown in Fig. 1(a). In addition to these two scenario, an additional simulation is done over a male phantom with the receiver array at the chest and the transmitter at the back with the right arm raised till shoulder level as shown in Fig. 1(b). This is done as an preliminary investigation for observing the effect of the arm movement on the AoA.

The distance between the elements of the receiver array is 60 mm ($\approx \lambda/2$ at 2.45 GHz). Square array is considered as it can estimate the angle from 0° to 360° in azimuthal plane whereas a linear array has ambiguity in separating $0^\circ - 180^\circ$ from $180^\circ - 360^\circ$. The phantoms are enclosed inside a perfectly matched layer (PML) boundary so that the signal transmission between the antennas are through the on-body creeping waves, through the reflection from the body parts (e.g. arms) or the combined effect of reflection and creeping waves. The simulated channel matrix in the frequency domain is formed by the S_{21} obtained by the simulation at 4 antenna positions at the receiver for 501 frequency points in 2.4 GHz to 2.5 GHz frequency band.

3. RESULTS AND DISCUSSIONS

It is assumed that the creeping waves are plane waves so that SAGE could be implemented. Moreover, the angular resolution of the AoA estimate for high resolution algorithms is limited by modeling error and noise. For four elements square receiver array, AoAs could have uncertainties at low signal-to-noise ratio (SNR) but here we have infinite SNR (as no noise is present in the simulations). Hence, implementation of SAGE is valid. The parameters of (1) for 10 MPCs are estimated using SAGE. Fig. 2 shows the estimated and the simulated impulse response for the case when the transmit antenna is located at the back of the phantoms. The figure shows good agreement between the SAGE estimated impulse response and the simulations. The estimated angle of arrival for the transmit antenna at the back, for both male and female phantom is shown in Fig. 3. The length of the line is proportional to the power received in that direction. The strongest component received for the male phantom is at 270° which could be traced to the creeping path going from the transmit antenna to the receiver array from the gap between the legs. Moreover, because of the symmetrical nature of the placement of the antennas, the other AoAs are symmetrical along the y-axis. However, for the female, the strongest component is at 257° which could be due to the change in the creeping path because of the presence of the breasts. Hence, difference in the direction of arrival due to the anatomical variation of male and female could be observed.

For the asymmetrical case, when the transmit antenna is located at the waist, for the male phantom, the strongest component is at 85° which could be traced to the path coming from back of the phantom and then creeping over the shoulder to reach the receiver array. The next strongest component is found to arrive at 339°. This path could be traced to path which gets reflected by the arm and then reaches the receiver array. For the asymmetrical female phantom case, the strongest component is at 310°. The possible path for this could be of the creeping wave which creeps over the abdomen and then creeps around the breast to reach the receiver array.

The strongest component for the male phantom with the right arm raised and the transmitter at the back is at 272°, which is 2° more than the normal position of the phantom. Table 1 presents the AoA for the first five strong components. It can be seen that for the asymmetric case, the AoA for is no longer symmetrical along the y-axis. Moreover, the anatomical variations between the male phantom and the female phantom results in different AoA for the same location of the receiver-transmitter pair. Variations in AoA can be observed between the normal phantom and the phantom with the arm raised for the same position of the transmitter.

Table 1: AoA for the First Five Strong Components

MPC	M Tx Back	F Tx Back	M Tx Waist	F Tx Waist	M Arm Raised
1	270	257	85	310	272
2	139	134	339	96	139
3	49	233	43	0	229
4	43	317	252	221	134
5	227	49	139	36	44

M: Male, F: Female

The AoA versus delay distance for 10 MPCs is presented in Fig. 4. Delay distance gives the idea that for a particular direction, what could be the possible path length taken by the MPC. As for e.g., the creeping wave path along 270° for the Tx at back of the male phantom is approximately 1.3 m. Normalized power w.r.t. to the strongest component is also shown in the figure.

It should be noted that the AoA will not be fixed to these estimated values for different scenarios like sitting position, walking position etc. for a particular on-body channel and numerous scenarios have to be simulated to find a range of the AoA for a particular on-body channel. Nevertheless, the possibility of using SAGE for the AoA estimation is shown. Moreover, the algorithm confirmed that the AoA will be different for same Rx-Tx placement for a male and a female due to anatomical variations. Apart from fixed beam antenna for reliable on-body communication, another possible application of the algorithm could be in real-time estimation of AoA and then steering the antenna beam towards the directions of the strong components.

4. CONCLUSIONS

The directional analysis of the on-body propagation channels using a high resolution algorithm, SAGE, was presented. The analysis was done on the data obtained from the simulations on a male and a female human phantom. Both symmetrical and asymmetrical placement of the transmitter antenna w.r.t. the receiver array was considered. As expected, in the symmetrical case the angle of arrival is symmetrical along the strongest component. However, the anatomical variations between a male and a female results in different angle of arrivals. For the asymmetrical placement of the antennas, the variations in the angle of arrival for male and female are more significant. Some angle of arrival suggests that the wave might be received after being reflected from the arms. Hence, in the scenario where person wearing the WBAN devices are walking/moving, arms movement will change the AoA for different time instants as observed by AoA estimates for the phantom with an arm raised till shoulder.

Since the communication between the on-body devices is through creeping waves which have exponential attenuation with the distance, knowledge of the AoA for the on-body channels could be beneficial in designing the antenna with a better radiation pattern so that the gain of the antenna/antenna array is high in the directions from where the strong components are received. Thus, directional analysis of the on-body propagation channels is beneficial in designing a reliable wireless link between the on-body devices.

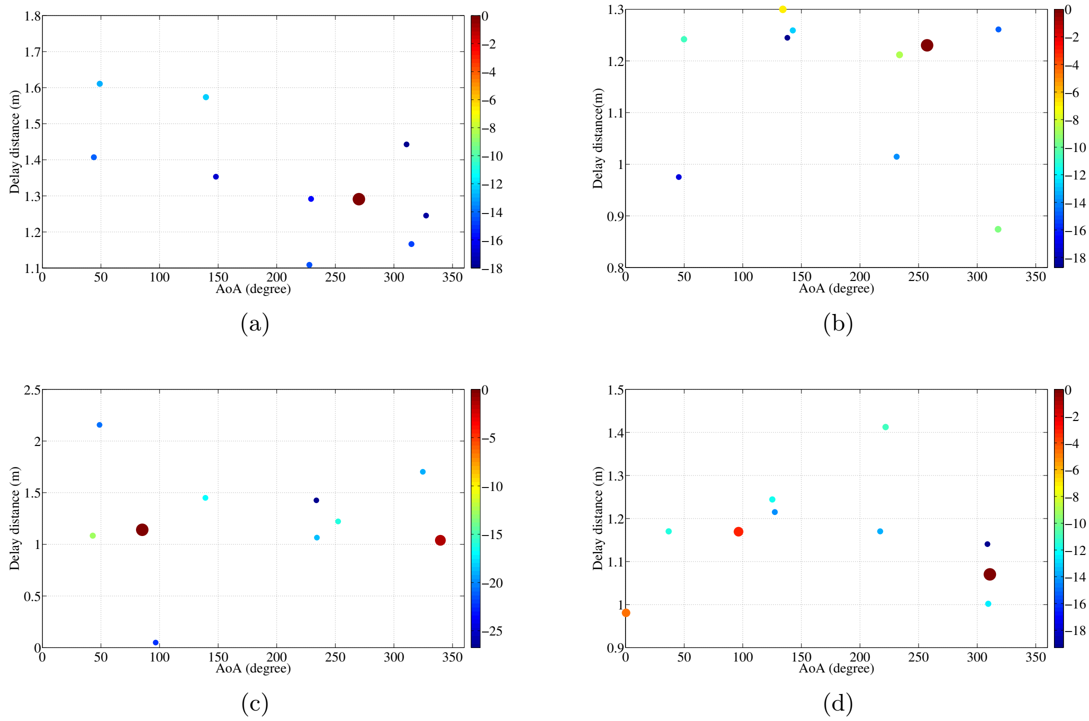

Figure 4: Delay distance versus AoA for the 10 MPCs (a) Tx at back for male (b) Tx at back for female (c) Tx at waist for male (d) Tx at waist for female. The power is proportional to the size and color of the circle shown in the colorbar. The colorbar shows the normalized power w.r.t. the strongest component.

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