34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Effect of Frequency, Body Parts and Surrounding on the On-Body Propagation Channel Around the Torso

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***Abstract*— Wearable medical devices can be positioned around the torso for monitoring of critical health parameters. The signal transmission between them is through a wireless link over an on-body propagation channel. In this paper, the effect of some factors which could influence the propagation channel around the torso as: (a) frequency of operation (b) positions of the arms (c) material of a chair used, have been investigated. Moreover, a comparison between the link loss around the torso of a full body phantom and a truncated torso phantom has been done. It is found that the frequency of operation and the positions of the arms have a significant influence on the channel. The difference between the link loss of a full body phantom and a truncated phantom is found to be minimal, indicating a possibility of using a truncated torso for a faster simulation. The results presented in the paper gives an insight in to the influence of arms and the frequency of operation on the propagation channel around the torso and thus would be beneficial for designing a reliable wireless link.**

I. Introduction

Wireless Body Area Network (WBAN) has emerged as a key technology in medical support and health monitoring. IEEE 802 has established a task group named IEEE 802.15.6 for the standardization of WBAN [1]. WBAN can be broadly divided into two categories [2]: (a) wearable (b) and implantable. Wearable WBAN is gaining popularity because of its non-invasive nature [3] and can be used as a consumer electronics even by healthy persons such as sportsmen and athletes. Recently there has been an increased research interest for the investigations of the propagation channel between different wearable WBAN devices. Both statistical and deterministic propagation/link loss model are being developed for various WBAN scenarios [4]-[9].

In [7], we have presented an analytical link loss model for the propagation around the human torso for the case where the wearable WBAN devices are on the opposite side but at the same level of the torso. The model was based on the elliptical approximation of the cross-section of the torso. It was validated through a truncated torso of a heterogeneous phantom. The arms were excluded from the simulation domain. The influence of the different arm positions on the radiation pattern from an implanted radio transmitter has been presented in [10]. The effect of the arm movements on UWB on-body channels is discussed in [11]. In this paper, we have extended our investigation to include the influence of the whole body and different positions of the arms on the propagation channel around the torso. Simulations are done over the homogeneous phantom models with the tissue properties of that of muscle at 2.45 GHz. SEMCAD-X [12] which uses the finite-difference-time-domain (FDTD) method [13], is used for the simulations. It is found that the effect of the whole body on the link loss is minimal whereas the positions of the arms have a significant effect on the link loss. The propagation channel around the torso might get influenced when the person having WBAN devices are sitting on the chair. For this reason, the effect of a chair with different material like metal and wood is also investigated. The link loss at other frequency bands used for the on-body medical devices (403.5 MHz, 5.8 GHz, 60 GHz) is calculated using the analytical model.

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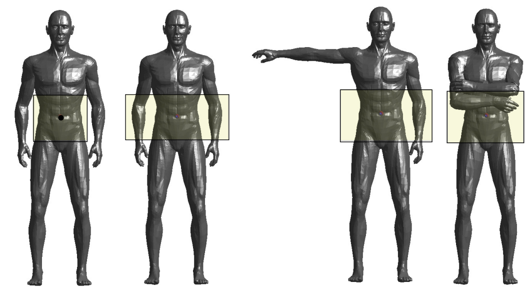

(a) (b) (c) (d)

Fig. 1. (a) Without arms (b) With arms (c) Right arm raised (d) Folded arms. These pose were used for the simulations. The simulation boundary to truncate the model is also shown with a black boundary around the torso. The level of the antenna is shown in (a) with a black dot. Apart from these models, a whole body simulation was also done.

II. Different Arm Positions of the Phantom

The human phantoms are created in the 3D-CAD software called POSER [14] and then imported into SEMCAD-X. The phantoms are assigned homogeneous muscle tissue properties at 2.45 GHz (permittivity = 52.7 and conductivity = 1.7 S/m). Using a homogeneous phantom is an effective approximation as the heterogeneity of the tissues of the various organs inside the body has minimal effect on the on-body propagation [15]. The different positions of the arm for the phantom used in the simulations are shown in Fig. 1.

III. Simulation Scenarios

For investigating the effect of the arms and the whole body on the link loss around the torso, five different scenarios are considered. They are: (1) Whole body in the simulation domain (2) Truncated body without arms, Fig. 1(a) (3) Truncated body with arms on the side of the waist, Fig. 1(b) (4) Truncated body with one arm raised till shoulder level,

Fig. 1(c) (5) Truncated body with the folded arms, Fig. 1(d). The truncation of the body is achieved by negative padding along the transverse plane of the phantom in SEMCAD. The simulation boundary is uni-isotropic perfectly matched layer (UPML). An antenna designed and optimized to work in 2.45 GHz band [16] is used as transmit and receive antenna. The transmit antenna is fixed at the back and the receive antenna in moved along the abdomen. The antenna positions for Fig. 1(b) is shown in Fig. 2. The elliptical approximation of the torso as described in [7] is also shown. The elliptical approximation gave a = 144 mm and b = 93.6 mm.

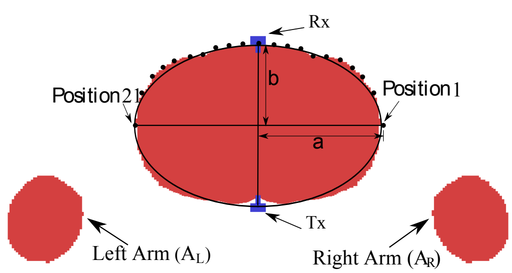

Fig. 2. The cross-section of the torso at the level of the antennas when the arms are at the side of the waist. The positions of the receive antenna is shown by the black dots. The elliptical approximation of the torso is also shown where a = 144 mm and b = 93.6 mm. The cross-section of the arms are also visible. The left arm (A_L) is close to position 21 and that the right arm (A_R) is close to position 1.

IV. Link Loss Model

The signal transmission between the WBAN devices located on the opposite side of the torso takes place through the creeping waves. The link around the torso can be described by clockwise and anti-clockwise creeping waves. The link loss, $LL_n|_{\text{dB}}$ at the n^{th} receiver position without considering the arm effect for perfectly matched antennas can be written as [7]:

$$\begin{aligned} LL_n|_{\text{dB}} &= -10\log_{10}\frac{P_{RX}}{P_{TX}}\bigg|_n \\ &= -10\log_{10}\left[\frac{G_{RX}G_{TX}\lambda^2}{4\pi^2}\left(\left|\frac{e^{-L_{cn}}}{d_n}e^{-jkd_n}+\right.\right.\right. \\ &\left.\left.\left.\frac{e^{-L_{acn}}}{p-d_n}e^{-jk(p-d_n)}\right|\right)^2\right] \end{aligned} \quad (1)$$

where p is the perimeter of the elliptical fit of the torso and d_n is the length of the clockwise path at the n^{th} receiver position. $k = \frac{2\pi}{\lambda}$ is the wave-number in free space, λ being the wavelength. L_i with $i = c$ or ac is the complex attenuation factor over an elliptical surface of the clockwise and the anti-clockwise creeping waves respectively [17].

V. Results

A. Effect of frequency of operation

The common frequency bands used for the on-body devices are the Medical Device Radiocommunications Service (MedRadio) band ($401-406$ MHz) created by FCC in 2009 [18] and the ISM bands (2.45 GHz and 5.8 GHz). Recently there has been growing interest for 60 GHz band for the on-body communication [19]. The S_{21} for all these different frequency bands calculated using (1) is shown in Fig. 3. The link loss is given by $-S_{21}$ in dB scale. $G_{TX} = G_{RX} = 0$ dBi is assumed for all frequency bands so that the difference in the link loss is caused by frequency and not by the type of the antenna. Two things can be observed from the figure. Firstly, as expected, the link loss increases with the increase in the frequency. Secondly, the number of fading dips increases with the frequency. Fading dip is a decrease in the received power level caused by the destructive interference of the clockwise and the anti-clockwise creeping waves. Moreover, the position of the fading dips also varies with the frequency. If possible, the placement of the WBAN devices should be avoided at these positions.

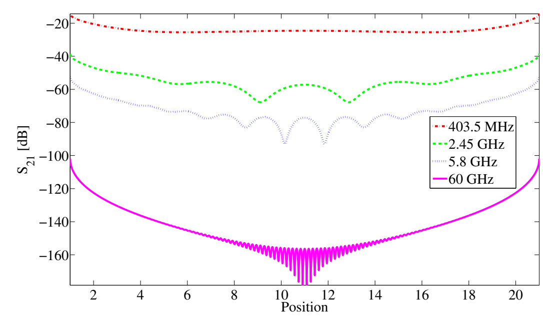

Fig. 3. S_{21} for different frequency bands

B. Effect of the Whole body

The plot for simulated S_{21} for the whole body and the truncated body with the arms at the side is shown in Fig. 4. It can be seen that the difference in the link loss is within 2 dB. This is because the creeping wave suffers an exponential attenuation with the distance [4] . Hence, most of the power is concentrated in the clockwise and the anti-clockwise path (the two shortest paths) around the torso at the level of the antennas whereas the contribution from the creeping waves which creeps over the shoulder or other body parts and then reaches the receiver is minimal. Hence, using a truncated model which reduces the simulation time is a good approximation for estimating the link loss around the torso.

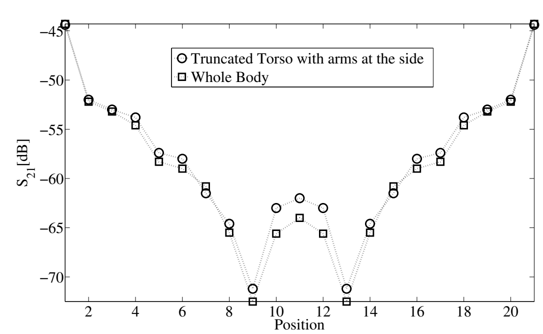

Fig. 4. Simulated S_{21} for whole body vs. truncated body

C. Effect of the Arms

In the following subsections, effect of the various positions of the arms on the link loss around the torso will be presented. The case as shown in Fig 1(a), where the arms are excluded from the simulation domain can be equivalent to the positions where both the arms are raised above the level of the antenna. Similarly, the case of Fig. 1(c) can be equivalent to all those positions where one arm is raised above the level of the antenna. The link loss for these scenarios is shown in Fig. 5.

1) No Arm and Both Arms: In Fig. 5, the simulated S_{21} for the case when the arms are excluded (Fig. 1(a)) is shown with dotted line with stars and that with both arms (Fig. 1(b)) is shown with dotted line with circles. It also shows S_{21} ($-LL_n$) obtained from (1) with $G_{TX} = G_{RX} = -7.3$ dBi with the solid line. It should be noted that the gain of the receiver antenna varies at different positions but for analytical model gain at position 11 is considered. Difference between the FDTD simulations and the analytical model can be reduced by using proper gain values at the different receiver position as discussed in [7]. It can be seen that the presence of arms can decrease the link loss by $6-8$ dB. This is because of the waves from the transmitter which gets reflected from the arms, adds up at the receiver, increasing the received power level.

2) Only One Arm: The simulated S_{21} for the raised right arm as in Fig. 1(c), is also shown in Fig. 5. The effect of the reflection from the arm can clearly be observed. The link loss is lower at the left side of the body (position $12-21$) where the left arm (A_L in Fig. 2) is present as compared to right side of the body. Moreover, no fading dip occurs at the position 13 and the fading dip occurring at position 9 shifts towards position 8. Thus, presence of arm at one side of the torso changes the link loss as well as the positions of the fading dip.

3) Folded Arms: The effect of the folded arms on the link loss is shown in Fig. 5 with dotted line with triangles. S_{21} for the folded arm is approximately same as that for the torso without arms. The reason for this is again the same that the contributions from the creeping waves above the level of the antenna is minimal and most of the power received by the receiver is from the creeping waves at the level of the antenna or from the reflections, if arms are present at the side of the waist. Moreover, the analytical model gives the worst case link loss.

VI. Effect of Material of the Chair

There can be a scenario when the patient wearing the WLAN sensors around the torso is sitting on a chair. In such cases, the material of the chair may affect the link loss around the torso. To investigate such a case, a simple model of the back-rest of a chair was added behind the phantom as shown in Fig. 6. The torso posture while sitting is assumed to be same as that of the standing case for simplicity. Two types of the material are considered for the chair's back-rest: (a) metal (b) 20 mm thick wood with permittivity $= 2.1$ and conductivity $= 0.0085$ S/m. The chair's back-rest is at

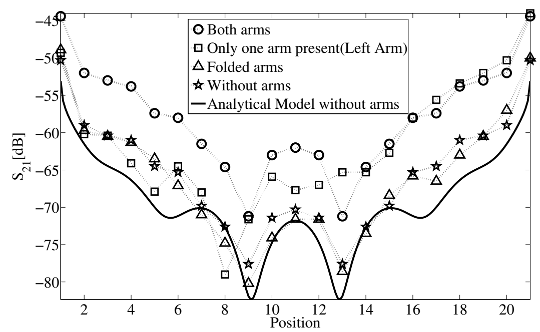

Fig. 5. S_{21} for different arms positions

approximately 8 cm away from the transmit antenna which is on the phantom's back. S_{21} for the case when no chair is present and when a chair with metal/wood is present is shown in Fig. 7. It can be seen that the presence of a metallic chair can decrease the link loss, again because of the reflections whereas a wooden chair has minimal influence.

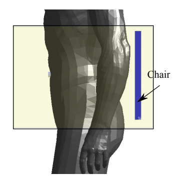

Fig. 6. Phantom with a simple model of the chair's back-rest

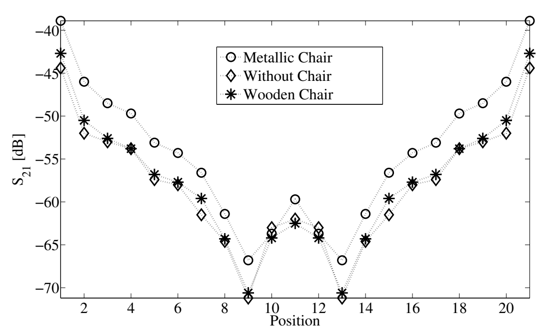

Fig. 7. S_{21} with vs. without chair

VII. Conclusions

The effect of the whole body and the various positions of the arms on the link loss for the propagation channel around the torso were presented. It was found that the whole body had a minimal influence on the link loss around the torso. Hence, using a truncated torso model for a faster simulation is an effective approximation. A decrease of about 8 dB in the link loss was observed due to the reflections occurring from the arms when both the arms were present at the side of the waist. Another conclusion that could be drawn from this observation is that there will be probably a temporal variation in the link loss while a user of the WBAN devices is walking. When only one arm was present, the link loss decreased at the side where the arm was present. On the other side, the link loss was almost same as that without the arm with a shift in the fading dip position. The folded arms at the chest level had a slight influence on the link loss. Hence, the link loss without the arms present at the side of the torso is the worst case deterministic link loss. This was also verified with the presented analytical model based on the elliptical approximation of the torso where the influence of the arms was not included.

The effect of a chair made up of metal and wood on the channel was also investigated. A metallic chair decreased the link loss because of the reflections whereas a wooden chair's effect on the link loss was minimal. The frequency of operation had a significant influence on the link loss around the torso. The link loss increased with increase in the frequency. Moreover, the number and positions of the fading dips also varied with the frequency.

This paper gives an insight in to the influence of various body parts on the propagation channel around the torso. With the knowledge of the link loss in various scenarios, the sensitivity of the WBAN devices placed around the torso could be decided, such that they work reliably in all different scenarios. Moreover, for a reliable signal reception, placement of the WBAN devices should be avoided at the positions of the fading dips. Hence, the results presented in the paper would be beneficial for designing a reliable wireless link for WBAN devices placed around the torso.

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