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PAPER

Numerical Channel Characterizations for Liver-Implanted Communications Considering Different Human Subjects

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SUMMARY This paper presents a numerical study of the wireless channel characteristics of liver implants in a frequency range of 4.5–6.5 GHz, considering different digital human phantoms by employing two inhomogeneous male and female models. Path loss data for in-body to on-body and in-body to off-body communication scenarios are provided. The influence of respiration-induced organ movement on signal attenuation is demonstrated. A narrower range of attenuation deviation is observed in the female model as compared to the male model. The path loss data in the female body is between 40–80 dB which is around 5–10 dB lower than the male model. Path loss data for the in-body to off-body scenario in both models suggest that in-body propagation is the main component of total path loss in the channel. The results demonstrate that channel characteristics are subject dependent, and thus indicate the need to take subject dependencies into consideration when investigating in-body communication channels.

key words: body area network, implantable biomedical devices, path loss model, propagation, ultra-wideband (UWB), wireless biotelemetry

1. Introduction

Organ transplants are now a common part of medical therapy [1], and the most frequently transplanted organs are the liver, kidney, heart, and pancreas. In particular, recent medical advances have resulted in the universal recognition of liver transplantation as the standard medical treatment for end-stage liver diseases, acute fulminant hepatic failure, hepatocellular carcinoma, and hilar cholangiocarcinoma [2], [3]. However, despite the increase in the number of liver transplant procedures being carried out at this time, the number of donated organs continues to be limited. It has therefore become extremely important to minimize the failure rate of liver transplantation. Reportedly highest during the two-week period immediately after surgery, minimizing failure rates remains a challenge. Current standard methods for monitoring transplanted organs, such as daily blood testing and tissue biopsies, do not allow prompt intervention and are often too slow to detect potential complications [4]. A

Fig. 1 An overview of the liver-implanted wireless monitoring system.

liver-implanted wireless monitoring system can be a practical solution to this challenge by offering real-time and continuous monitoring that enables timely detection before severe damage occurs, which can ultimately assist in reducing graft loss and mortality [4].

Figure 1 shows an overview of a liver-implanted wireless monitoring system in an example case scenario. A liver-implanted wireless device is attached to the transplanted liver surface. This system monitors physiological data such as hepatic perfusion and oxygenation levels, the efficacy indicators of a transplanted liver [4], and transmit them to an on-body device. The on-body device then acts as a transmission hub that wirelessly relays the data to personal devices of patients, and doctors, and to servers in the hospital. This wireless monitoring application can provide real-time monitoring for reporting the physiological status of a patient to medical personnel [1].

To facilitate the telemetry link between the implanted medical device and the exterior device, communications of this kind typically operate in frequency bands such as Medical Implant Communication Service (MICS) (402–405 MHz) [5], [6]. Despite the good propagation behavior and the potential use of reasonable antenna size in MICS, its data rate is limited [6]. As a result, ultra-wideband (UWB) technology is considered a favorable approach [7]–[10]. UWB signal transmissions are allowed in the Federal Communications Commission's authorized frequency range (3.1–10.6 GHz) when the equivalent isotropically radiated power (EIRP) is kept below -41.3 dBm/MHz [11]. Several studies have presented the viability of high data rate UWB communication for implantable devices [12], [13]. Its ability to provide high data rate transmissions can accommodate various medical applications such as implantable drug delivery [14] and micro robots for in-body biopsy and treatment procedures [15]. Also, the physical size of an implantable antenna can be significantly reduced due to the high frequency used in UWB. This, together with the simple transmitter structure, means that the small and lightweight implanted

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devices can be easily manufactured. Furthermore, the device longevity can be enhanced because of the low power consumption of UWB technology, and, in addition, the removal of implanted devices is not necessary because of the potential use of biodegradable materials, thus further reducing risk to the patient.

However, the high attenuation of UWB signals inside the human body causes degradation of system performance, and therefore causes difficulty in implementing in-body UWB wireless communications. Hence, a thorough understanding of the propagation channel characteristics within the UWB frequency range is required to accomplish reliable wireless communication links.

The in-body propagation channel is strongly related to the location of implants as different channel links involving different organs and tissues lead to variations in channel characteristics. In-body propagation of UWB channels in different locations is reported in the open literature, for example in the chest [16], brain [17] and the torso [18], [19]. However, to the best of our knowledge, no study of liver-to-skin UWB propagation channels exists in the open literature.

Our previous work has investigated the channel characteristics and confirmed the feasibility of liver-implanted wireless communications using UWB channels; simulations and experimental measurements were conducted using simplified multilayer human phantoms, as well as numerical studies using one digital inhomogeneous male model to consider the effect of respiration-induced organ movements on signal attenuation for the in-body to on-body communication scenario [20]–[23]. The objective of the current paper is to expand our investigations to numerically study the influence of body size and composition on the channel characteristics of liver-implanted wireless communications at the lower part of the UWB range. Male and female human phantoms are used for modeling two standard implant communication scenarios, namely in-body to on-body (IN2ON) and in-body to off-body (IN2OFF). Quantitative data sets of path loss (PL) in both scenarios are presented. The results show that PL in the female model is lower than in the male model. Also, more variation in attenuation due to upper abdominal organ movement during normal respiration was found in the male model in comparison to the female model. Our investigations of the IN2OFF scenario suggest that in-body propagation is the dominant contributor to total PL in the channel. The rest of this paper is structured as follows: the configuration of the numerical study is introduced in Sect. 2; Section 3 presents and discusses the outcomes of the study; and Sect. 4 presents the key findings along with concluding remarks.

2. Configurations of the Numerical Investigation

All simulations were carried out using CST Microwave Studio software. Our objective was to characterize the liver-implanted propagation channel, not to propose any suitable in-body or on-body antennas, hence, an existing small tapered-slot UWB antenna, fabricated in the Antenna Measurement Laboratory at Queen Mary University of London

Fig. 2 (a) Geometry of the low profile tapered-slot UWB antenna used in this study fabricated by Queen Mary University of London [24]. (b) the UWB antenna covered by a material mimicking liver tissue inserted in a square-shaped case.

(see Fig. 2(a)), was used in our simulations [24]. The antenna was inserted in a square-shaped case (see Fig. 2(b)) and used as an in-body and on-body antenna throughout the investigations reported in this paper. For better impedance matching, the antenna was partially inserted in the liver tissue equivalent material, as shown in Fig. 2(b). The case dimensions were 14.9 mm $\times$ 23.4 mm $\times$ 10.7 mm and its thickness was 0.5 mm. Two different numerical human models were used in the simulations: a male model named Taro (height 173.2 cm, weight 65 kg, body mass index 21.7) and a female model named Hanako (height 160.8 cm, weight 53 kg, body mass index 20.4). Both are Japanese models developed by the National Institute of Information and Communication Technology [25]. Liver and skin tissue mimicking materials were added to the liver and skin to create a flat surface between the antenna case and the tissues in both Taro and Hanako body model scenarios. The following two implanted wireless communications scenarios were considered here.

1. In-body to on-body communication scenario (IN2ON): one antenna (referred to as in-body antenna) was implanted on the liver surface and the other antenna (referred to as on-body antenna) was placed on the skin surface as shown in Fig. 3 (Hanako) and Fig. 4 (Taro).
2. In-body to off-body communication scenario (IN2OFF): one antenna (referred to as in-body antenna) was implanted on the liver surface and the other antenna (referred to as on-body antenna) was located in the air at d_{off} (distance from the skin surface) = 2 mm and 5 mm, as shown in Fig. 5 (Hanako) and Fig. 6 (Taro).

The in-body antenna was fixed in position on the liver tissue, 24 mm from the front skin surface and 74 mm from the left side skin surface in the Hanako model, as illustrated in Fig. 3 and Fig. 5. It was fixed at 31.5 mm from the front skin surface and 44 mm from the left side skin surface in the Taro model, as illustrated in Fig. 4 and Fig. 6. The on-body antenna was moved horizontally along the reference line in steps of 20 mm up to a distance of 80 mm. During normal respiration, the largest movement of the liver is reported to be around 40 mm [26], and so the same approach was repeated up to 40 mm vertically above and below the reference line to consider the effect of organ movement on signal attenuation. Both the horizontal and vertical orientations of antennas were

Fig. 3 Cross-section view of the Hanako model sliced at a height of 1116 mm (as shown in Fig. 7), displaying locations of the on-body and in-body antennas in the IN2ON simulation setup.

Fig. 4 Cross-section view of the Taro model sliced at a height of 1170 mm (as shown in Fig. 8), displaying locations of the on-body and in-body antennas in the IN2ON simulation setup.

Fig. 5 Cross-section view of the Hanako model sliced at a height of 1116 mm (as shown in Fig. 7), displaying locations of the on-body and in-body antennas in the IN2OFF simulation setup where two scenarios of d_{off} (distance from the skin surface) = 2 mm and 5 mm were configured.

Fig. 6 Cross-section view of the Taro model sliced at a height of 1170 mm (as shown in Fig. 8), displaying locations of the on-body and in-body antennas in the IN2OFF simulation setup where two scenarios of d_{off} (distance from the skin surface) = 2 mm and 5 mm were configured.

Fig. 7 3-D model of Hanako displaying simulation area and all on-body antenna locations. The on-body antenna in both vertical and horizontal orientations was horizontally moved from its initial location in steps of 20 mm up to the distance of 80 mm and its vertical positions were changed in steps of 20 mm up to 40 mm above and below the reference line.

Fig. 8 3-D model of Taro displaying simulation area and all on-body antenna locations. The on-body antenna in both vertical and horizontal orientations was horizontally moved from its initial location in steps of 20 mm up to the distance of 80 mm and its vertical positions were changed in steps of 20 mm up to 40 mm above and below the reference line.

considered in the simulations. Fig. 7 and Fig. 8 illustrate all positions of the on-body antenna for the Hanako and Taro models respectively. Thereafter, numerical results of S-parameter were collected at various distance values between the two antennas.

3. Numerical Results and Analysis

3.1 IN2ON Scenario

A. Return Loss Results

The return loss results of the in-body and on-body antennas within the frequency range of 4.5–6.5 GHz for the Taro and Hanako models are shown in Fig. 9 and Fig. 10 respectively. The same return loss results of the Taro model scenario have been previously presented in [22]. It can be seen that although the return loss characteristics of the in-body and on-body antennas are different for each model, they still gave good performance. For the in-body antenna, the difference in results could be attributed to the different surrounding tissues. For the on-body antenna, the difference in results could be due to the differences in body shape between the male and female models given that the female body has more curvature compared to the male body.

Fig. 9 Return loss results of the in-body antennas within the 4.5–6.5 GHz frequency range for the Taro and Hanako models.

Fig. 10 Return loss results of the on-body antennas within the 4.5–6.5 GHz frequency range for the Taro and Hanako models.

B. Influence of Respiration-induced Organ Movement

Numerical S_{21} results were recorded at various locations of the on-body antenna for both the Taro and Hanako models, as shown in Fig. 11 and Fig. 12 respectively. The same S_{21} results of the Taro model scenario were presented in [22]. Fluctuations in S_{21} along the vertical axis can be observed for both model scenarios. These S_{21} deviations indicate that the level of signal attenuation inside the human body is affected by organ movement. Across both model scenarios, the widest range of variation was around 30 dB for overall horizontal locations. It was observed that larger attenuation deviations occurred at each horizontal location in the Taro (male) model as compared to the Hanako (female) model.

C. Path Loss

From the obtained S_{21} data, the path loss (PL) for both models was calculated using the following expression:

$$PL = -\{|S_{21}|\} \text{ in decibels.}$$

The path loss model of the in-body channel as a function of propagation distance was then obtained using the least-squares fitting method. The fitted curve for the path loss model was applied using the following equation:

$$PL(d) = PL_{0,dB} + 10n \log_{10} \frac{d}{d_0} + S_{dB} \quad (1)$$

where d is the separation distance between the in-body and

Fig. 11 S_{21} results as a function of horizontal movement distance of the on-body antenna from its initial position at different locations on vertical axis for Taro model scenario [22].

Fig. 12 S_{21} results as a function of horizontal movement distance of the on-body antenna from its initial position at different locations on vertical axis for Hanako model scenario.

on-body antennas in millimeters and d_0 is the reference point of the distance between implant and front skin surface, that is 31.5 mm and 24 mm for Taro and Hanako model respectively. PL_0 is the path loss at the reference point d_0 , n is the path loss exponent. S is the shadowing term representing deviation from the mean path loss. This term is a normally distributed random variable with zero mean and standard deviation, σ_{dB} . Figure 13 illustrates the path loss data as a function of the logarithmic distances of antenna separation and its linear fitted curve. The corresponding path loss parameters are summarized in Table 1. Overall, the path loss in the Taro model scenario is higher than in the Hanako model scenario. This could be attributed to the fact that the female body typically contains a higher quantity of low loss tissues such as fat (which has a conductivity of 0.21 S/m at 4.5 GHz) in comparison to the male body which typically contains more muscle tissues (which has a conductivity of 3.51 S/m at 4.5 GHz). Since the Hanako model has a smaller body size, its liver area is more compact, and so the shadowing term or the deviation of path loss in Hanako is less than in Taro.

Fig. 13 Comparison of path loss of Taro and Hanako models with respect to the logarithmic in- and on-body antenna separation distance.

Table 1 Path loss parameters of the Taro and Hanako models for the IN2ON case scenario.

Path loss parameters	d_0 (mm)	PL_0 (dB)	n	σ (dB)
Taro	31.5	51.3	6.1	7.1
Hanako	24	47.7	4.6	6.1

Fig. 14 Return loss results of the on-body antennas at the 2-mm distance from body surface within the 4.5–6.5 GHz frequency range for Taro and Hanako model cases in the IN2OFF case scenario.

Fig. 15 Return loss results of the on-body antennas at the 5-mm distance from body surface within the 4.5–6.5 GHz frequency range for Taro and Hanako model cases in the IN2OFF case scenario.

3.2 IN2OFF Scenario

A. Return Loss Results

In practice, an on-body device does not have to be placed di-

Fig. 16 Path loss of the simulated channel as a function of the logarithmic in- and on-body antenna separation distance for the IN2OFF case scenario (Taro model).

Fig. 17 Path loss of the simulated channel as a function of the logarithmic in- and on-body antenna separation distance for the IN2OFF scenario (Hanako model).

rectly on the skin surface, but can also be attached to clothes, for example. In this scenario, there would consequently be small gaps between the on-body device and skin surface which would lead to more attenuations. Therefore, for this IN2OFF scenario, the on-body antenna was kept in the air at 2 mm and 5 mm separation from the body surface. The return loss results of the on-body antenna for both the Taro and Hanako models show good behavior within the 4.5–6.5 GHz band as shown in Fig. 14 and Fig. 15 respectively. The characteristics of the return loss results were slightly different between the models which may be due to the curvature of body surface.

B. Path Loss

Figure 16 and Fig. 17 illustrate the path loss data of the IN2OFF channel as a function of logarithmic-distance and its linear fitted curves for the Taro and Hanako model scenarios obtained using (1). The path loss parameters for the 2 mm and 5 mm off-body distances are shown in Table 2. It is observed that the path loss data for both 2 mm and 5 mm off-body case scenarios are similar to the path loss data in the IN2ON channel scenario. This suggests that the total path loss for the IN2OFF channel is mainly attributable to in-body propagation.

4. Conclusions

In this paper, the numerical channel characteristics of a wireless communication link between a liver-implanted de-

Table 2 Path loss parameters of Taro and Hanako models for the IN2OFF case scenario.

Taro	d_0 (mm)	PL_0 (dB)	n	σ (dB)
2 mm off-body	33.54	49.9	7.7	5
5 mm off-body	36.54	51.1	7.4	5
Hanako	d_0 (mm)	PL_0 (dB)	n	σ (dB)
2 mm off-body	26	45.7	5.3	6.4
5 mm off-body	29	47.2	4.5	4.6

vice and an on-body device are presented with consideration of different digital human subjects in a frequency range of 4.5–6.5 GHz. Two realistic numerical human models, Taro (male) and Hanako (female) were used to compare the influence of different body shape and composition on the liver-implanted channel characteristics. The fluctuation of signal attenuation due to respiration-induced organ movements was observed in both model scenarios. Path loss models for the two cases have been provided for both the in-body to on-body and the in-body to off-body channels. The obtained results show that a difference of body size (around 6% difference in body mass index) can lead to a difference of nearly 10% in path loss. This indicates that channel characteristics are subject specific and this should therefore be considered in future research. The path loss characteristic presented in this paper is inevitably antenna dependent, as is most path loss characteristics reported in wireless body area network propagation research. However, the quantitative information and path loss models presented here provide useful insights into channel behavior by comparing two different human models in in-body to on-body and in-body to off-body scenarios. This can be a practical tool for link margin calculation, and for performance evaluation of in-body wireless telemetry systems in the liver area using UWB technology. Consequently, these original findings serve as an important initial step in developing innovative healthcare monitoring applications using implantable devices.

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