UWB Characteristics of Creeping Wave for RF Localization around the Human Body

Jin Chen, Yunxing Ye, Kaveh Pahlavan
Center for Wireless Information Network Studies
Department of ECE, Worcester Polytechnic Institute
Email: {jchen3, yunxing, kaveh}@wpi.edu

Abstract— **There is much current interest in wireless networking of sensors deployed on and around the human body, in view of many potential applications for health monitoring. In this paper, we conducted ultra-wide-band (UWB) measurements around human body and a phantom in order to develop angle based channel models for body area network (BAN) and to compare the measurement results in these two environments. By analyzing certain channel parameters such as, time-of-arrival (TOA), distance-measurement-error (DME), received signal strength (RSS) and total path-loss, we discuss the influencing factors when the signal traveling around the human body. We also analyze the influence of the human body on TOA ranging accuracy.**

Keywords- body area network, channel model, localization

I. INTRODUCTION

Ultra-wide-band (UWB) technology has attracted much attention recently since the announcement of spectrum allocation from 3.1 to 10.6GHz for unlicensed UWB communication applications by the Federal Communication Commission (FCC) [1]. Although product based on UWB Technology have not met the expected results, the UWB channel characteristics have been very helpful for RF localization science and technology[2]. One of the promising applications for UWB technology is Body Area Network (BAN) communications, because UWB is a low-power, high data rate technology. Meanwhile, due to the high center frequency of UWB, the antennas for this band are always small in size, which is a desirable property for body worn devices.

An important aspect of the development of BAN at UWB is the characterization of the physical layer of the network, including the estimation of the path loss around and through the human body, and delay spread, which are important for communication applications, and time of arrival (TOA) of the first multipath component (MPC) and the received signal strength (RSS) of the first MPC.

There are some BAN applications require the location information of sensors inside or on the surface of human body. A typical one is the wireless capsule endoscopy (WCE), during the process of examination, the capsules inside human body transmit RF signals to the out surface of human body, and doctors want to know the accurate location of the pill from the information carried by the RF signal. The current technology for locating these sensors is based on received signal strength (RSS) ranging [3], but the accuracy is far from satisfaction. We envision more precise ranging techniques such as TOA ranging will be employed to increase the accuracy of localization results. Unfortunately, there are only a few researchers noticed this trend and no around or inside human body measurements has been conducted to develop the UWB channel model for localization applications.

In this paper, we focus on developing UWB channel models based on the measurement results around human body and a phantom for RF localization in BAN applications. A phantom which mimics the human torso environment is employed to study the effect of human tissue non-homogeneity of localization accuracy.

This paper is organized as follows. Section Ⅱ describes the measurement scenario and measurement equipment. In section Ⅲ, we analyze and compare the measurement results around human body and phantom. The metrics include TOA, DME, RSS and total path-loss. Section Ⅳ presents the conclusion.

II. MEASUREMENT SETUP AND SCENARIO

The measurement setup is configured for conducting the measurements around the human body and a phantom to develop UWB channel model for various MPC parameters such as TOA, RSS and total path-loss[4].

All the measurements presented in this paper were conducted in an RF anechoic chamber, a shielded room having dimensions 2.32m ×2.41m×2.29m[5]. The interior structure of the chamber greatly attenuates any MPCs reflected from walls, and also isolates the experimental setup from RF signals existing outside the chamber.

An E8363B Vector Network Analyzer(VNA) is employed to sweep the frequency from 3-10GHz. The measurement parameters are listed in Table 1.

Table 1: Measurement parameters

VNA setup parameters	Value
Frequency band	3-10 GHz
Number of points	1601
Transmission power	0 dBm

We measured the transfer function S21 and the measurement results are stored in a PC which is wirelessly communicated with the VNA. After obtaining the frequency data, we first apply a Hamming window to the data to reduce the effect of side lobes and then use the Inverse-Chirp Z transform to convert the frequency data to a time domain impulse response. After that, we apply a peak detection algorithm to extract the MPC from the time domain impulse response and analyze the parameters in time domain.

Two antennas are used during the measurement campaign. The transmitter antenna is fixed on the front surface of the human body or a phantom, as point 0 shown in Figure 1(c). The distance between the human body and the antenna is about 10mm, which is caused by the clothes. The distance between the phantom and the antenna is also 10mm, because the cable is fixed next to the phantom, and in this way there is a room between the antenna and the phantom. The antennas used in this paper are model SMT-3TO10M-A UWB patch antennas from SkyCross corporation[6]. The operating frequency range of these antennas is between 3.1 and 10.0 GHz. The antennas and the VNA are connected by shielded coaxial cables. To eliminate the power loss from the connection part of the coaxial cables we use tin foil as better shielding to cover the cables and the connection part between the antenna and the VNA.

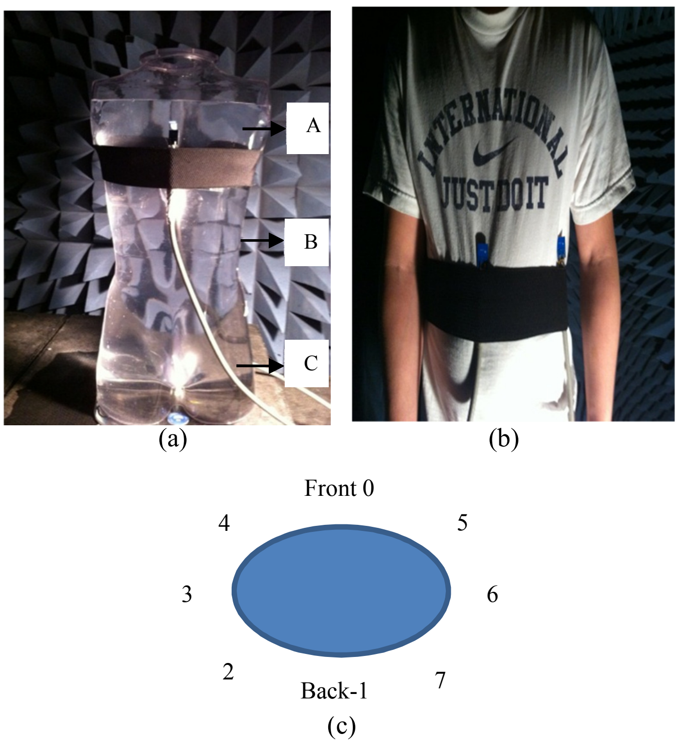

Fig. 1: Measurement environment: (a) Measurement around a phantom; (b) Measurement around human body; (c) Location of the measurement points every height

Figure 1(a) shows the measurement setup around a phantom. The phantom we used in the measurement is from the Phantom Laboratories[7]. The surface of the phantom is made by cellulose acetate butyrate. During the measurement, the phantom is filled with water in order to simulate the simplified environment of human body because the main component of human tissue is water and the electrical characteristics of human tissue is close to water. We conducted 20 measurements at each receiver location at each height to study the statistics of MPC parameters. The total length from the shoulder to the waist of this phantom is 45cm, hence we did the measurements every 15cm which are shown in the Figure 1(a) as Height A, Height B and Height C. The distance between every two adjacent points is same. We also did the similar measurements around the human body, shown in Figure 1(b). During these human body measurements, the person is in a standing position in the chamber and tries to keep static during the process of data collection.

III. Measurement results and discussion

For the RF localization applications around the human body, we develop angle based channel models for TOA and gain of the first arrived MPC, which is for the TOA ranging based localization technique, and for the total path-loss which is for RSS based localization.

Generally speaking, there are three kinds of paths for RF signals traveling from the transmitter antenna to the receiver antenna. The first kind of path is the direct path(DP). Signal travel through the water in the phantom or human tissue in real body to reach the receiver antenna. These paths are not the dominant path in BAN scenario because of the gain reduction through water or body tissue. We tend to neglect these paths in practice because they are too weak to be differentiated from the background noise [8]. The frequency range in this paper is 3-10 GHz in which the diffraction is much stronger. So the second kind of path is diffraction around the human body or a phantom which is also called ‘creeping wave’. We will focus our discussion on these paths due to most availability of them in the BAN scenario. The third kind of paths is the reflections from the environment which can also be neglected because we did all the measurements in the chamber [5].

A. Time of arrival(TOA):

TOA is an important ranging metric for localization in BAN. TOA of the first peak of the creeping waves can be directly converted to distance information as the input to localization estimation algorithms.

Firstly, we measure the TOA in free space as a reference distance between the two antennas to find out the system bias. Measurement in free space which is also in the chamber can only find the peak of direct path. In our case, the actual distance between the transmitter and the receiver antennas is 23.5cm. By analyzing the result we can find the measured distance by the VNA is 31cm. In this way, the system bias Δt is 0.25ns.

During this part of the measurements, the phantom is filled with water, which can be treated as homogeneous tissue. Because of the differences in the distance from point 0 to the same point in different height, we decide to use angle instead of distance as the reference. Table 2 shows the angle from the transmitter antenna to receiver antenna. We have three groups of data obtained in different heights at the same angle, so we calculate the arithmetic square root of the times of arrival of the first peak of creeping waves. In this way, we can compare the measured TOA with the expected TOA using angle based model.

Table 2: Angle from P_0 to P_n

P_0 to	P_1	P_2	P_3	P_4	P_5	P_6	P_7
Angle	180	132	90	48	312	270	228

The expected TOA of the first peak can be treated as transmissions time around the surface of human body or a phantom which can be calculated using the distanced-based model, (1). In (1), D_{on} means the distance from transmitter antenna to the receiver antenna, c means the transmission speed of signals via air and Δt means the system bias which has been measured in free space. In our measurement, we calculate the expected TOA of the first peak using the angle based model, as shown in (2).

$$\text{Expected TOA} = \frac{D_{on}}{c} + \Delta t; \qquad (1)$$

$$\tau(\theta) = \begin{cases} \frac{1}{2} \times \frac{\theta \times \pi}{180} + \Delta t; & 0 < \theta < 180 \\ -\frac{1}{2} \times \frac{(\theta - 360) \times \pi}{180} + \Delta t; & 180 < \theta < 360 \end{cases} \qquad (2)$$

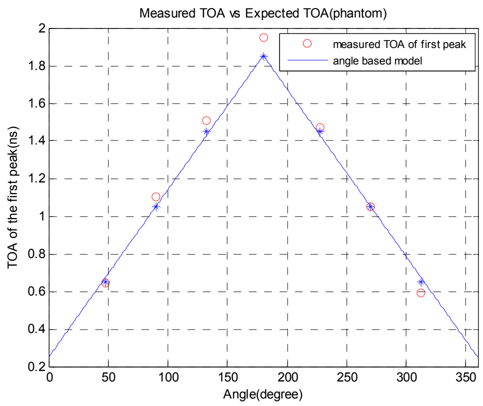

Fig. 2: Measured TOA and expected TOA around a phantom

In Figure 2, the measured TOA and the expected TOA are shown from which we notice that the measured TOA and the expected TOA are very close. The first peak of the creeping waves in different points in different heights is always the strongest peak in our measurements.

Figure 3 shows the TOA of the first peak around human body. The main path we are interested in is the creeping waves, which may be influenced by the environment of the surface. The expected TOA of each angle is also used the angle based model. But phantom is homogeneous and has smooth surface. From the measurement results we can find the TOA error of the human body is larger than that of the phantom which is reasonable.

B. Distance-measurement –error(DME):

The accuracy of localization based on TOA is highly related with DME. We calculate and plot the DME to figure out its distribution around the human body and a phantom. The definition of DME is as follows [9]:

$$\varepsilon = \hat{d} - d \qquad (3)$$

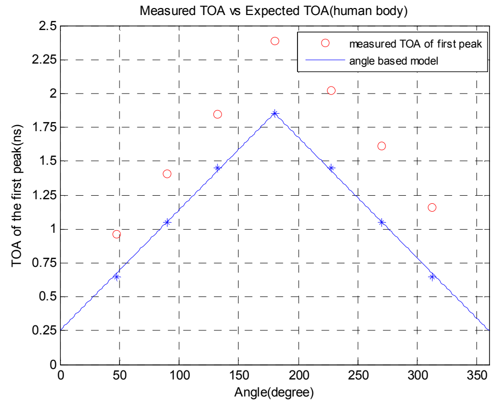

Fig. 3: Measured TOA and expected TOA around human body

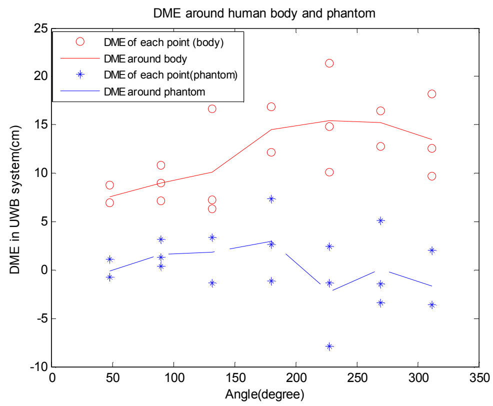

Fig. 4: DME around human body and a phantom

In (3), $\hat{d}$ means the measured distance between the transmitter antenna and the receiver antenna, and d means the expected distance between the transmitter antenna and the receiver antenna. The best achievable accuracy of a distance estimate $\hat{d}$ from TOA satisfies the following inequality [10]:

$$\sqrt{Var(\hat{d})} \geq \frac{c}{2\sqrt{2}\pi\sqrt{SNR}\beta} \qquad (4)$$

$$\beta \triangleq \left[\int_{-\infty}^{\infty} f^2 |S(f)|^2 df \Big/ \int_{-\infty}^{\infty} |S(f)|^2 df\right]^{1/2} \qquad (5)$$

In (4), c is the speed of light, SNR is the signal-to-noise ratio, and β is the effective signal bandwidth which is defined in (5). Because the receive power of the first peak of the creeping waves is from -45dBm to -90 dBm, and the power of noise is close to -120dBm. In this way, SNR is from 75dB to 30dB. β equals to 7 GHz. Based on (4), the standard deviation is less than 0.11cm which is much smaller than the minimum measured standard deviation, 2.32cm. So the inequality (5) established.

From Table 3, we can find that the mean of DME around a phantom is close to 0. And using the distribution fitting tool of Matlab, the DME around a phantom is according with Gaussian distribution which is shown in Figure 5(a). The mean of DME around human body is 12.06cm, and we can be treated as a 12.06cm bias. After eliminate this bias, we compare the CDF of DME around human body and Gaussian distribution as shown in Figure 5(b), which shows a good agreement. Based on our measurement results we can find TOA of the first peak of the creeping waves is a very useful metric for RF localization in BAN.

Table 3: Mean and standard deviation of DME around a phantom and human body

	DME	
	Mean	Std.
Phantom	0.34	3.44
Human body	12.06	4.46

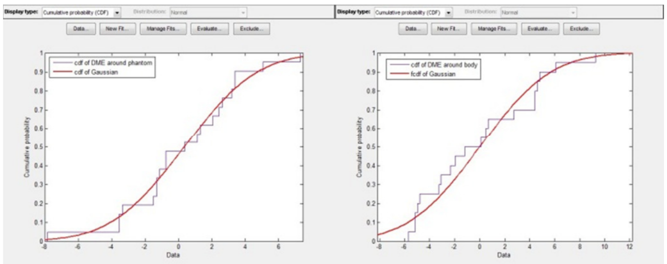

Fig. 5(a): CDF of Gaussian and CDF of DME around phantom; Fig. 5(b): CDF of Gaussian and CDF of DME around human body

C. RSS of the first peak:

RSS of the first peak is an important factor in RF localization. But only using RSS of the first peak to estimate the location, the result may have a big error with the actual location. However, if the first peak can be captured accurately, we can estimate the location of the transmitter antenna with the help of the TOA.

In our measurement, the selected points around the human body and a phantom are symmetrical, and in this way we only use one side data when analyze the RSS. Based on the measurement results, we can build an angle based channel model for the path-loss of the first peak as follows:

$$P_{f-dB}(\theta) = P_{dB}(\theta_0) - \gamma_1(\theta - \theta_0) \quad (6)$$

Table 4: Parameters of angle based channel model for first peak path-loss

	Phantom	Human
$P_{dB}(\theta_0)$	41.25 dB	48 dB
γ_1	16dB/rad	18dB/rad
θ_0	0.2415 rad	0.2415 rad

Figure 6 and Figure 7 show the measured path-loss and angle based channel model we built of the first peak path loss around a phantom and the human body.

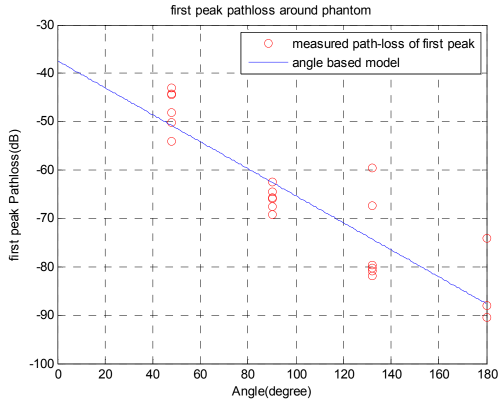

Fig. 6: Path-loss of the first peak around a phantom

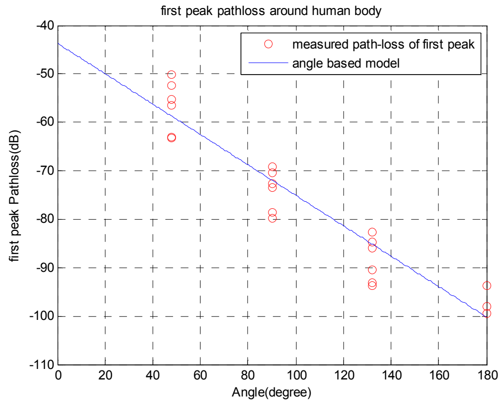

Fig. 7: Path-loss of the first peak around the human body

$$P_{dB} = P_0 + 10n\log(d) \quad (7)$$

Based on our measurement results above, we can calculate the path-loss gradient n based on the (7) which is built in [11]. After fitting the measurement results we can get the path-loss gradient n of the first-peak around a phantom and human body equal to 5.8 and 7.27. And the path-loss gradient n of total path-loss around a phantom and human body equal to 4.47 and 6. The first path-loss gradient is lager than that of the total path-loss. This result is reasonable. All these results about the path-loss grsdient are clearly shows in Table 5.

Table 5: Path-loss gradient n in different situations

	Path-loss gradient n	
	Phantom	Human body
First-peak	5.8	7.27
Total path-loss	4.47	6

D. *Total path-loss:*

A channel model has been built in [8], which is suitable for UWB and based on the distance between the transmitter antenna and the receiver antenna. Formula (8) is the distance based channel model. In our measurement the distance between the antenna and human body or a phantom is 10mm, so n is 6.0, d_0 is 0.1m and P_{odB} is 45.8dB. In this way, we can have the expected total path-loss of each point using this distance based channel model.

$$P_{dB} = P_{0dB} + 10n \log\left(\frac{d}{d_0}\right) \quad (8)$$

Channel models for wireless communication around human body along the angle between the transmitter antenna and receiver antenna in the radio frequency of 400MHz, 900MHz, and 2.4GHz have been built in [12]. However, there is no angle based channel model for UWB. Accourding to our measurment results, we can build an angle based channel model for RF localization around human body in UWB as (9). The parameters for this formula are shown in Table 6.

Figure 8 shows the measured total path-loss, the distance based channel model total path-loss and angle based channel model total path-loss around a phantom and the human body.

$$P_{dB}(\theta) = P_{dB}(\theta_0) - \gamma_1(\theta - \theta_0) \quad (9)$$

Table 6: Parameters of angle based channel model for the total path-loss

	Phantom	Human
$P_{dB}(\theta_0)$	36.25 dB	44.25 dB
γ_1	13dB/rad	16dB/rad
θ_0	0.3115 rad	0.3115 rad

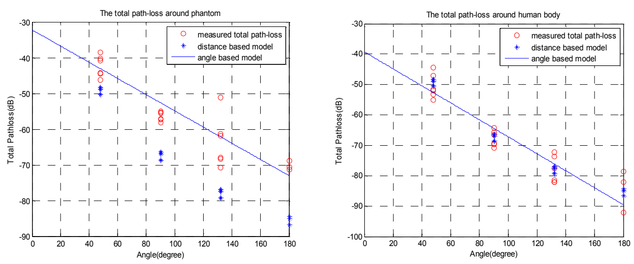

Fig. 8: Measured total path-loss, distance based and angle based total path-loss around a phantom and human body

IV. CONCLUSION

We conducted the measurements of TOA and RSS around the human body and a homogeneous phantom, and compared the results obtained in these two environments. Based on the measurement results, the angle based channel model for the RSS of the first peak of the creeping waves has been built which can be used capture the first peak accurately. We also built the angle based channel model for the TOA of the first peak of the creeping waves which can be used for RF localization in BAN. We found that the DME using measured TOA of the first peak around human body and the phantom exhibited Gaussian distributions. The TOA of the first peak measured around the phantom corresponds more closely to the predicted TOA value than that measured around the human body. Finally, we were able to construct an angle based channel model for total path-loss in each of the two environments.

V. REFERENCE

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