RF Localization Inside Human Body

Enabling micro-robotic navigation for medical applications

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***Abstract*— In this paper we introduce issues relevant to understanding of the human body as a medium for radio frequency (RF) navigation of smart robots travelling inside the body for wireless medical applications. We provide the results of Cramer Rao Lower Bound (CRLB) for in-body localization using received signal strength (RSS) and we highlight challenges demanding further research for attaining more precise localization inside body using time-of-arrival (TOA) techniques.**

Keywords-body area networks, localization, radio propagation, wireless health,

I. INTRODUCTION

Engineering innovations are often motivated by metaphors described in science fictions. Later on science and technology evolves to implement these fictions into marketable devices. . The wireless networking industry was motivated by the captain Kirk's communicator in the 1960's science fiction Star Trek. This communicator was very popular in many presentations in the early days of wireless networking. After about half a century, modern smart phones are perhaps a close imitation of that fantasy. Smart phones are almost the same size and they allow multimedia communication presumably everywhere. However, not all the features of the Star Trek communicator are included in the smart phones, for example we are far away from beaming Mr. Spock whenever he is in serious trouble!

The body area networking industry may be affected by another 1960's science fiction, Fantastic Voyage, in which a space craft with its crew was shrunken to become a micro-device capable of traveling inside human body. That space craft lost its remote navigation capabilities and went through an unguided dramatic travel within the human body before it exits through tears from the eye. Today, endoscopy capsules are traveling digestive system of human body and people perceive other micro-robots to travel inside blood circulation of human being. We don't have the technology to shrink the people; however, we have enough of remote control capabilities that we can have robots do operation inside body without an operator inside the craft.

In the past decade miniaturization and cost reduction of semiconductor devices has allowed design of small low cost computing and wireless communication devices used as sensors in a variety of popular wireless networking applications and this trend is expected to continue in the next few decades. It is expected that a myriad of new applications designed around sensor technologies will emerge to stimulate the world economy for another round of industrial growth. One of the most promising areas of economic growth associated with this industry is the body sensor network that is also referred to as the body area networks (BAN) [1].

These networks are expected to connect wearable and implantable sensory nodes together and with the Internet to support numerous applications ranging from traditional externally mounted temperature meters or implanted pace makers up to emerging blood pressure sensors, eye pressure sensors for glaucoma and smart pills for health monitoring and precision drug delivery.

To support the growth of this industry, recently the Federal Communication Commission (FCC) has allocated specific bands for Medical Radio Communication Services (MedRadio) [2] and the IEEE 802.15.6 is formed to address the standardization aspects of these emerging technologies. The IEEE 802.15.6 models the characteristics of the radio propagation inside and around human body and defines wireless networking technologies for wearable and implanted sensor networks[3].

A number of technical challenges regarding size and cost, energy requirements, and wireless communication technology are under investigation and in the heart of these investigations is the understanding of radio propagation in and around the human body. In this paper we address issues relevant to understanding of the human body as a medium for radio frequency (RF) navigation of smart robots inside body.

Certainly for all BAN applications power efficient modulation and medium access control methods are needed in principle and a number of researchers are working on that topic [7]. The important and the fundamental issue presented in this paper is the localization of objects inside human body to assist the discovery of methods for navigating emerging micro-robots in wireless medical applications such as capsule endoscopy. This is a new field of research that is gaining some momentum [8][9].

Understanding the nature of signal propagation is the key to the design of efficient and low-power, low-cost communication systems and precise localization for the BANs. Therefore, the first step in research is to start a measurement and modeling

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program to understand the nature of signal transmission inside human body. Today, the existing literature in measurement and modeling for understanding the propagation in and around human body is fragmented and it does not pay attention to localization inside body for emerging applications such as localization of endoscopy capsules [10]. There is a need for research in understanding the behavior of RF signal propagation inside human body for localization applications.

Channel measurement and modeling for inside human body to support waveform transmission for RF localization is in its infancy. From innovative research point of view, measurement and modeling of radio propagation inside and around the human body offers unique challenges making this area very appealing for basic research. These challenges are raised by several specifics of the human body medium and its applications that are profoundly different from the traditional indoor radio propagation challenges. In the rest of this paper we first use an existing model for path-loss inside human body to calculate bounds on received-signal-strength (RSS)-based RF localization for capsule endoscopy application. Then we address challenges for more precise time-of-arrival (TOA)-based localization inside body by presenting some preliminary results and pointing to open issues demanding further research.

II. BOUNDS ON RSS-BASED LOCALIZATION

In this part of the paper we determine the bounds on the performance of RSS-based localization techniques for in-body RF devices. We use the existing channel models presented in [11]to determine the Cramer Rao Lower Bounds (CRLB) for the variance of the RSS-based localization [8] inside the body. The channel models are statistical channel models reported in the literature and we used 3D CRLB calculations in [12].

Results of the analysis using cooperative localization bounds for endoscopic wireless capsule as it passes through the human gastro-intestin (GI) tract is reported in [12]. In that work the CRLB variance limits on location estimators which use measured RSS are reported. Using a three dimension human body model from full wave simulation software and log-normal models for RSS propagation from organ implants to body surface, we calculated bounds on location estimators in three digestive organs: stomach, small intestine and large intestine. We provide analysis of the factors affecting localization accuracy such as external sensor array topology and number of capsules in cooperation. The simulation results show that cooperation among pills inside the GI tract have the potential to reduce the location error significantly.

A. Path loss model for GI track environment

The statistical implant to body surface path loss model used for calculating the CRLB of wireless capsule endoscopy (WCE) localization was developed by National Institute of Standards and Technology (NIST) at (Medical Implant Communication Service)MICS band [11]. The main components used for developing the model include: a three-dimensional human body model, the propagation engine which is a three-dimensional full wave electromagnetic field simulator, the 3D immersive & visualization platform and implantable antenna. The path loss in dB at some distance d between the transmitter and receiver can be statistically modeled by the following equation:

$$L_p(d) = L_p(d_0) + 10\alpha \log(d/d_0) + S(d > d_0) \qquad (1)$$

where d_0 is the reference distance, i.e. 50mm, and α is the path loss gradient which is determined by the propagation environment. For example, in free space $\alpha = 2$. As we already mentioned, human body tissue strongly absorbs RF signal. Therefore, a much higher value for the path loss gradient is expected. The random variable S is log-normally distributed around the mean which represents the deviation caused by shadowing effect of human tissue. The parameters of the implant to body surface path loss model are summarized in Table I.

TABLE I. CHANNEL PARAMETER USED FOR PERFORMANCE COMPARISON OF RSS-BASED COOPERTAIVE LOCALIZATION.

Implant to Body Surface	$Lp(d_0)$	α	σ_{dB}
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

where σ_{dB} is the standard deviation of shadow fading S. Note that there are two sets of parameters for path loss from deep and near surface implant to body surface. During our simulation, we use 10cm distance between the transmitter and receiver on body surface as the threshold for choosing the model. If the distance is less than 10cm, we use the near surface to surface path loss model, otherwise the deep tissue to surface model is used.

B. Simulation Results

We first evaluate the impact of the organ shape and location on localization accuracy. For the simulation, we fixed the number of receiver sensors to 32 and assume only one single capsule in each organ. We calculated the 3D-CRB for all the possible location points inside each organ (634 points for stomach, 1926 points for small intestine and 3334 points for large intestine).

Notice that the localization error for the capsule in the small intestine is apparently smaller than that in the large intestine. The average value of error for the small intestine environment is 45.5mm, while it is 49mm for the large intestine environment. The localization error for the capsule in the stomach has the lowest average value but distributed in a wider range compared to the errors in the other two environments. These observations can be explained by the geometric relationship between the sensor array and the organs. As we can see from Fig. 1, the stomach is located in the upper part of the receiver sensor array system, and its volume is the smallest among the three organs. Therefore, the localization error varies more in the stomach environment. The points located in the upper part of the stomach have a larger localization error value as they are far from the center of the receiver array system, while the points in the lower part of stomach have a smaller localization error value. The small intestine is located in the center part of human abdomen cavity and the lumen is more centralized compared to the large intestine. Therefore, the

localization error inside the small intestine is smaller than that in the large intestine.

We then investigate the impact of number of receiver sensors on localization accuracy. For the simulation, we assume one capsule is located randomly inside each organ, and iteratively increased the number of receiver sensors. 12000 simulations were carried out (3 different organs, 4 different numbers of receiver sensors and 1000 simulations per organ). The result is shown in Fig. 2a.

Notice that the localization error decreases a lot when the number of receiver sensors increase from 8 to 16 and from 16 to 32, but not much from 32 to 64. Therefore, 32 receiver sensors is the optimal choice considering the cost and accuracy requirement together.

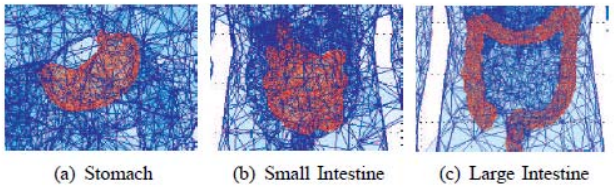
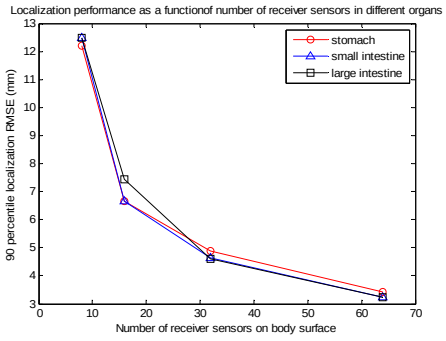
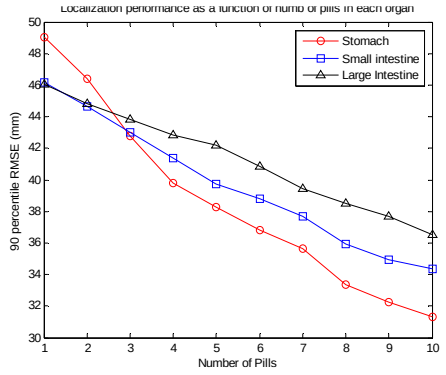


Figure 1 Performance Evaluation Scenario.

Subsequently, we analyze the effect of cooperation among pills on localization accuracy if multiple pills are sent into the digestive system and they can measure the signal from each other.



(a)



(b)

Figure 2 Performance Evaluation Results.

The result is shown in Fig. 2bNotice that cooperation helps most in the stomach environment as the localization error drops faster with an increase in the number of pills in cooperation.

III. CHALLENGES IN TOA-BASED LOCALIZATION

The important difference between propagation inside human body and the overall indoor propagation is that the medium for propagation inside the body is close to liquids, which have substantially different conductivity than the air which is the main medium for the indoor radio propagation. In addition, inside human body offers a non-homogeneous environment with non-geometric boundaries for radio propagation, while indoor is a non-homogeneous environment with fairly geometric boundaries for radio propagation. Inside a typical indoor environment most of the propagation time is spent through the air and the second important medium are the walls that have geometric shapes.

These features allow us to construct simpler radio propagation mechanism such as ray-tracing to describe the radio propagation in indoor environment using ray optics methods [13]. Inside human body is a non-geometric and non-homogeneous medium for radio propagation that will not allow application of simple ray tracing techniques. Conductivity of the propagation inside different organs, bones and the mussel tissues are also widely different posing a challenge for the analysis of time of flight for the signal that is commonly used for ranging using TOA of the received signal.

Indoor environment is a very complex propagation mediums for localization as well [14], but we can easily measure the wideband radio channel characteristics using a network analyzer and develop empirical statistical models for the TOA [15]. In radio propagation analysis inside the human body we cannot simply place antennas inside to collect empirical data for statistical radio propagation modeling. In indoor areas we use the time of flight of the signal to measure the distance between the transmitter and the receiver by multiplying the time of flight with the speed of radio wave propagation in the air that is the same as speed of light. Since the human body is a non-uniform liquid medium the speed of radio wave propagation is different from the speed of light and it also differs in various organs.

In this section we present some preliminary results and point to open issues in three specific areas for research related to TOA-based localization inside human body.

A. TOA Ranging in Non-Homogeneousity Human Body

The most accurate ranging for localization used in popular applications such as GPS is the TOA ranging. In traditional TOA localization applications the time of flight of a transmitted pulse with a sharp peak is measured at the receiver and distance is estimated by multiplying the time of flight with the velocity of propagation that is the same as velocity of light. This works because radio wave propagates in the air that is a homogeneous environment with a uniform permittivity. Human body is a non-homogeneous medium and permittivity of different organs are different and that causes a new source of ranging error. The ranging error is often caused by bandwidth

limitation and SNR limitation. Propagation velocity inside human body is expressed as a function of the relative permittivity:

$$v(\omega) = \frac{c}{\sqrt{\varepsilon_r(\omega)}}, \qquad (2)$$

where velocity is a function of permittivity and the permittivity is a function of the frequency of operation. On the other hand, the human body is formed by various organs with complex structures. Each organ has different characteristics of conductivity and relative permittivity. Inside human body, received signal is also distorted through the multipath channel caused by the refraction at the boundary of different tissues. Therefore, TOA ranging inside human body is very challenging.

The goal of our study in this area is modeling of the TOA ranging error caused by lack of information of the real propagation velocity inside human body. In some current literature, Kohno etc. [16] propose a TOA localization algorithm by using the average permittivity of all the tissue and organs to estimate the propagation velocity.

The ranging error is defined as:

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

where d is the actual distance and $\hat{d}$ is the estimated distance. Considering the total distance travelled through the body is added by the distance in each organ or tissue, the total distance can be expressed as:

$$d_{total} = d_1 + d_2 + \ldots + d_n, \quad (4)$$

where d_1 to d_n are the distances travelled in each organ or tissue. In reality, people often use average permittivity of human body to estimate the average propagation velocity inside human body, which is

$$\bar{v} = \frac{c}{\sqrt{\bar{\varepsilon}_r}}. \qquad (5)$$

Therefore, the estimated distance is expressed as:

$$\hat{d} = \hat{\tau}\bar{v} = (\hat{\tau}_1 + \hat{\tau}_2 + \ldots + \hat{\tau}_n)\frac{c}{\sqrt{\bar{\varepsilon}_r}} = \sum_{i=1}^{n} \frac{d_i}{v_i}\frac{c}{\bar{\varepsilon}} = \left(\frac{d_1}{c/\sqrt{\varepsilon_1}} + \frac{d_2}{c/\sqrt{\varepsilon_2}} + \ldots + \frac{d_1}{c/\sqrt{\varepsilon_n}}\right)\frac{c}{\bar{\varepsilon}} \qquad (6)$$

The difference between d_{total} and $\hat{d}$ is the ranging error that we are interested in . We simulate the human body in the 2D space which is a cross section of human torso shown in Fig. 3. If we put a transmitter and receiver on the surface of the body, the direct path would go through several different organs with different permittivity. Fig. 4 shows our preliminary results on the relation between the distance and estimated distance using average permittivity of the human body.

B. Simulation of Waveform Transmission Inside Body

In parallel with the measurement and analysis of the ranging error inside human body we also need to analyze the wideband characterization of human body using Finite Difference Time Domain (FDTD) simulations. The research being carried out is based on the application of localization and hence, the results are more concentrated towards the waveform transmission properties of the channels.

Both in the actual measurements and the software simulation, two dipole antennas in the 900 MHz band were placed 50 cm apart and the frequency response of the medium between the antennas was plotted for a bandwidth of 100MHz. This plot was then used to find the impulse response using the chirp z-transform function in Matlab. After this a person with height 172 cm and weight 156 lbs was made to stand between the two antennas and a human body model with similar characteristics was placed in the High Frequency Simulation Software (HFSS), between the two antennas . The impulse response for this new channel was also plotted much in the same way as before and the comparative results are shown in Fig. 6 [17]. The side faces of the radiation box in the HFSS simulations were assigned concrete as their material and the front and back faces were assigned the radiation boundary to imitate the environment of the lab.

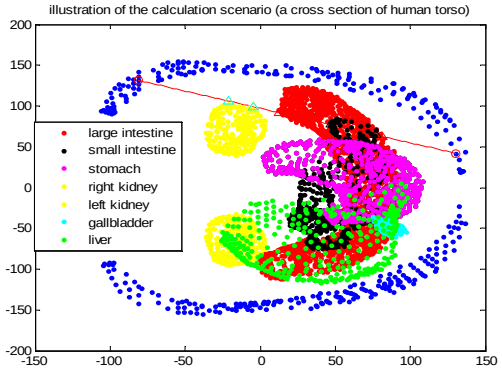


Figure 3 Typical Simulation Scenario in 2D.

From the measurement taken without the body, the TOA of the first path was calculated to be 1.70 ns, which roughly translates to about 51 cm - an error of 1 cm from the actual distance. The same value from the HFSS simulation came out to be 1.95 ns, which roughly translates to 58 cm, indicating an error of about 7 cm from the measurement. The TOA of the first path from measurements taken with the body came out to be 2.00 ns, translating into 60 cm, which means the human body added an error of 9 cm in the measurements. But the simulation with the body showed the TOA of the first path to

be 1.70 ns, again an error of 9 cm from the measurements but in the other direction.

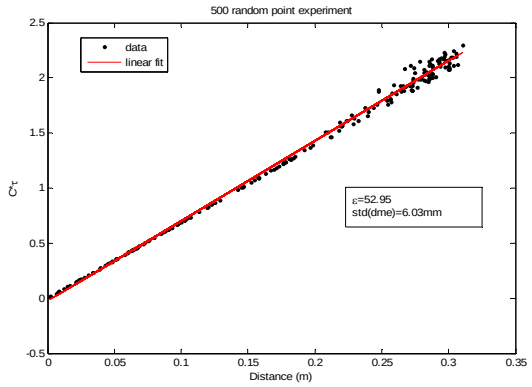


Figure 4 TOA Ranging Error Caused By Human Body Non-homogeneousity.

From Fig. 5, the root mean squared (RMS) delay spread of the first three paths for the measurements without the body came out to be 4.12 ns and that of the simulation without the body came out to be 3.97 ns; a difference of just 0.15 ns. When the body was added to the measurement setup, the RMS delay spread was calculated to be 3.79 ns, the same value for the simulation with the body came out to be 3.32 ns; an error of about 0.47 ns. Hence even the RMS delay spread of the HFSS simulation was very close to that of the actual measurements, rendering little doubt that it is a valid mean to simulate the wideband profile of a channel.

The main issue with using HFSS for these simulations is that it takes between one to five days to run one simulation. To eliminate this problem we wrote a FDTD solver for the human body in MATLAB. This solver was about sixty times faster than its HFSS counterpart.

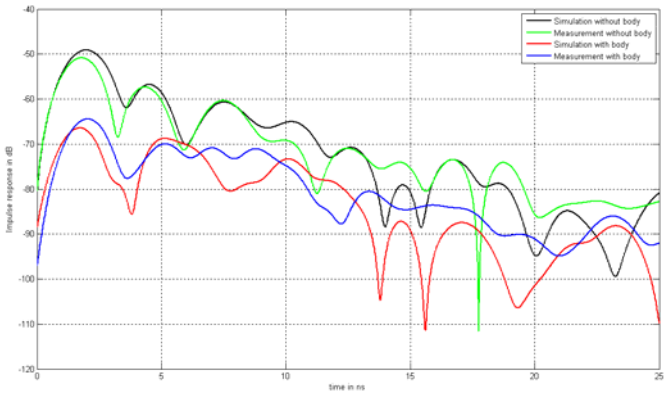


Figure 5 Impluse Response Obtained from the Two Simulated and Measured Channels.

Fig. 6 shows an FDTD simulation in MATLAB. This figure shows electric field distribution around the human body model with the transmitter and receiver sensors at positions *a* and *b* respectively, which are 5 cm apart[9] . As shown in the figure (right bottom), the TOA of the "first path" arrives at 0.2277 ns, which roughly translates to 6.83 cm, i.e. a distance measurement error of 1.83 cm. Notice, also, on the right side that the actual sensors for the simulation are not visible. This is because we tried to model a point source (with one FDTD cell) instead of a dipole antenna to eliminate the effects that maybe caused by impedance matching. However, it is not possible to model a perfect point (soft) source in MATLAB using FDTD, and that is why we can see the dip after the pulse is received. But if we plot the normalized power received, the negative region of that plot will be eliminated when the voltage is squared.

A number of such simulations were carried out with the transmitter kept at position a and the position of the receiver was varied from positions *b* to *j*. One such simulation was run where the position of the transmitter was at *d* and the receiver was kept at position *e*.

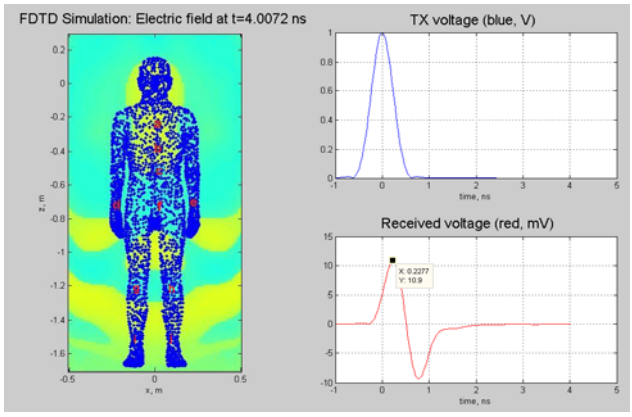


Figure 6 Left: Map of Where the Sensors were Placed; Right; Transmitted(top)and Received (bottom) Voltages vs. time.

To estimate the distance from the TOA plot we used the eq.2. From the slope of the TOA vs. distance line, the ε_r came out to be 1.336. Fig. 7 shows the distance measurement error plot obtained from the simulations carried out in [9]. It can be seen that the distance measurement error (given in millimeters) increases linearly with distance. Further research is being done to evaluate why such errors are being observed. Also, work is being done to compare the FDTD simulations with the HFSS simulations.

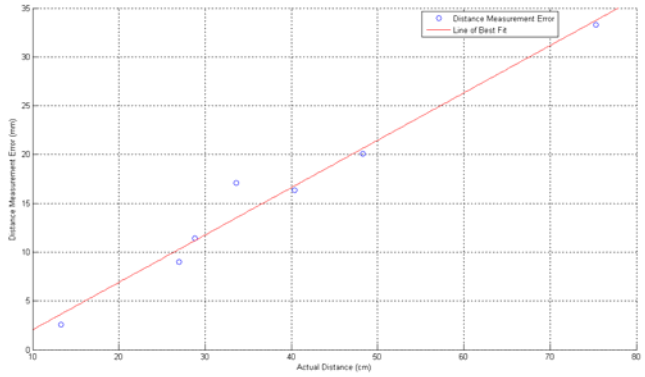


Figure 7 Distance Measurement Error from TOA for each sensor Position.

C. Effects of Human Body Movements

Effects of human body motion on RF propagation in and around the human body is a very important topic; because usually sensors are mounted on the torso, hands and feet, while a body mounted relay with larger size is mounted on the hips with the belt. In most popular envisioned applications for

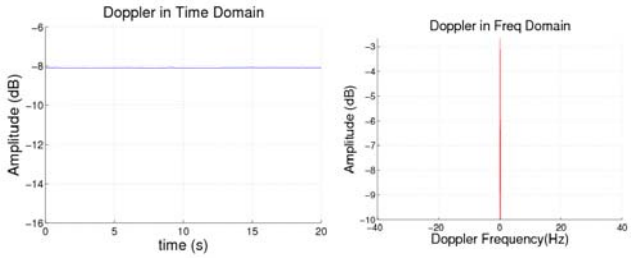
BANs the relay is used for communication to external access points connecting the network to the backbone Internet. The speed of motion of the sensors with respect to the relay and the external access point is quite different. In this part of our research we have started the analysis of these movements using the Doppler spectrum observed at the relay.Our objective is to model the Doppler spectrum for these motions and use it for motion detection. This, to the best of our knowledge, is lacking in the current literature. In this section we provide some preliminary results in this area. It is well known that an apparent change of frequency will occur in radar systems if there is a relative motion between the transmitter and the receiver. The maximum Doppler frequency shift f_m is determined by the velocity of the movement v_c and the wavelength, $\lambda = c / f_c$, with $f_m = \pm v_c / \lambda$, where $c \approx 3 \times 10^8$ m/s is the velocity of light and f_c is the transmission center frequency. The maximum value of f_m could be approximated from the Doppler spread B_D of the on-body to on-body communication.

From the narrowband measurements, reported in [18], we have the time domain response $H(f_c;t)$ received from an unmodulated sine wave transmitted at 400MHz, 2.25GHz and 4.5GHz respectively. After the Fourier transform of the time domain data $H(f_c;t)$, the Doppler spread $D(\lambda)$ could be calculated by applying a threshold of -10dBm in the frequency domain. For the on-body to on-body measurements, the Doppler spread varies approximately from 0.6Hz to 12Hz for scenario set S={Freq, Motion, RX, TX}, which is caused by a frequency set Freq={400MHz, 2.25GHz, 4.5GHz}, a motion set Motion={Stand, Walk, Jog} and antenna position sets RX={Right Hip} and TX={Back, Chest, Left Wrist, Left Ankle, Right Ankle}. And a set of Doppler spreads for a specific scenario [18] S1 = {{2.25 GHz}, {Stand, Walk, Jog},{Right Hip}, {Left Ankle}} is shown in Fig. 7, including both time domain response $H(f_c;t)$ and the corresponding response $D(\lambda)$ in frequency domain. The Doppler spreads for standing, walking and jogging motions are approximately 0.6758Hz, 2.929Hz and 11.19Hz for the communication links between left ankle and right hip.

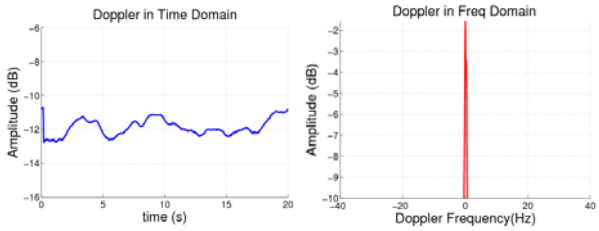
For the on-body to on-body measurements, the Doppler spread of standing position is usually below 1Hz since the channel fading is caused by small body movements. And the channel remains to be constant for a longer period. In the walking and jogging motions, the Doppler spread varies around 4Hz and 9Hz separately. As the transmission antenna moves far away from the receiver attached to the right hip, the Doppler spread rises in a small range.

A more specific estimation of the Doppler spread is the RMS Doppler bandwidth [19] RMS Doppler bandwidth is proposed to describe the Doppler shift by calculating the weighted signal power rather than simply an overall width of the spectrum in a more scientific method.

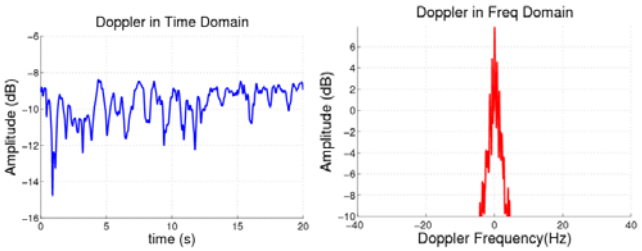
For the scenario set S, the RMS Doppler Bandwidth ranges from 0.6Hz to 4Hz. The reason for such difference comes from body postures, center waveform frequencies, and antenna positions on the test subject. In most of cases, RMS Doppler bandwidth is always below 1Hz for the standing still position, which shows a concentrated distribution of the received signal strength. While for walking and jogging motions, RMS Doppler bandwidth is much larger than that of standing still, and received signal strength is dispersedly distributed in the frequency domain. The Doppler spread in frequency domain in Fig. 8 shows the power distribution for scenario S1, where the width in frequency and the averaged power distribution keep increasing from (b) to (d).



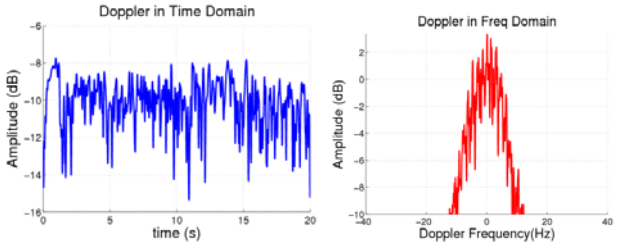
(a) Free Space



(b) Stand Still



(c) Walk



(d) Jog

Figure 8 Doppler Spread in Time Domain and Frequency Domain for Different Human Body Motions. (a) Free space (b) Stand Still (c) Walk on a Spot (d) Run on a Spot.

The movements of human body with different motions results in changes in the location of the sensors and their relative distance. Analysis of the effects of movements on the TOA-based ranging needs further research.

IV. CONCLUSION AND FUTURE RESEARCH

Navigation of micro-robots inside human body offers itself as a potential area of research with a number of useful and intellectually motivating research topics. In this paper we provided an overview of challenges in RSS- and TOA-based localization techniques for this area and we provided some preliminary results of research in several relevant topics. We showed that using multiple micro-robots one can use cooperative localization techniques to achieve accuracies around a few centimeters.

To find more precision we need to resort to TOA-based localization techniques that has its own challenges open for future research. We showed that assessment of the precision for ranging using TOA techniques the analysis of the effects of non-homogenous propagation medium inside human body that causes errors on the orders of millimeter. We also showed that analysis of the behavior of TOA ranging error requires numerical methods that has its own computational challenges demanding further research in that area and at last we discussed the analysis of human body movement and the need for further research in that area to analyze its effects on ranging using TOA techniques.

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