A Hardware Platform for Performance Evaluation of In-body Sensors

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Abstract— **Body area network is expected to be the next breakthrough invention with great potential due to miniaturization of wireless communication devices. One of the major challenges for design of sensor devices for wireless communications inside human body is the accessibility of the medium for performance evaluation. It is practically impossible to install a development module for a sensor inside the human body and when the sensor designed we need expensive procedure with physician supervisions to examine the performance of the sensors. In this paper, we introduce an interference controllable, repeatable real-time hardware platform for performance evaluation of a typical in-body sensor chipset used in most implant applications (Zarlink ZL70101 ADK operating at 402-405 MHz) utilizing an existing multipath channel emulator (Elektrobit PROPSim™ C8) to analyze the performance of the communication link between a sensor located inside the human body and a body mounted sensor. We show how link quality is analyzed by observing the packet reception rate under three different transmission alternatives.**

The ongoing development of Body Area Networks (BANs) in conjunction with advances in implantable medical devices is generating great interest in use of this interdisciplinary technology for improved health care, including patient monitoring, diagnostic procedures, and emergency treatment. However, the development of these applications has been hampered by the technical difficulties encountered in wireless transmission through and inside the human body. Prior research shows that signal propagation through and within the body is influenced by many factors, including differing dielectric properties of various organs, body shape and gender [1]. Consequently, knowing how signals propagate through and inside the body is challenging. So far, there is no widely-accepted model for wireless propagation in the human body, though various studies have been made for localization and communication applications, such as [2].

Several simulation software tools were developed for BANs communication purposes. Although these tools, such as HFSS [3] from Ansoft Corporation and FDTD [4] simulated in MATLAB, are very useful for accurately implementing channel models for signal propagation inside the human body, these software tools cannot be put to use for connecting real-world medical devices, which are necessary prerequisites to real-world field measurement. For such purposes, we have developed a real-time emulation hardware platform. For the device under test (DUT) we chose the Zarlink ZL70101 Application Development Kit (ADK) [5], and for multipath channel emulation we chose the Elektrobit PROPSim C8 system [6], which provides a repeatable, controllable body area propagation environment. Previous work on indoor communication and geolocation performance testbed using the PROPSim™ C8 is discussed in [7,8].

In BANs, link quality can be affected by many factors, including transmission power, packet size, maximum retransmission times, signal modulation scheme, and so on. In this paper, we focus on the impact of the choice of modulation scheme on link quality, by calculating packet reception rate (PRR) observed as a function of modulation choice and path distance.

This paper is organized as follows. Section II describes previous research on several statistical channel models which we adopted in our work. Section III describes our hardware platform and our study undertaken to prove its validity. Section IV presents link quality performance and comparisons. Finally, our conclusions are summarized in Section V.

I. CHANNEL MODEL FOR BANS

An accurate, verified propagation model is essential for BANs studies. A number of prior investigations have addressed statistical channel characteristics, including data gathered for in-animal and on-human body field measurements. Much work has also been done on simulation methods and models. These efforts have provided much useful data to assist the IEEE 802.15 standardization committee [9]. Kazunari Tai et al. [10] have inserted antennas into a pig's intestine instead of human body tissue. They drew the conclusion from measurements made along the pig's body center line that as a lossy medium, human tissue becomes a strong absorber of radio waves. The channel exhibited such a small delay spread that the multipath effect is negligible.

Kamran Sayrafian et al. [11] at the National Institute of Standards and Technology (NIST) introduced a path loss model as shown in Equation (1) with center frequency 403.5 MHz, modeling the human body using different dielectric parameters for different organs in simulating a 3D full-wave electromagnetic field in HFSS. PL represents path loss, d is the distance between the transmitter and receiver, S is shadow fading which subjects to Gaussian distribution here. The simulation modeled four near-surface implants and two deep-tissue implants placed inside a virtual male human body as transmitters. Their general statistical path loss model is described in Table I, providing the NIST model parameters for different channel conditions.

For BANs, nodes situated away from the human body should also include free space path loss and additional loss caused by

$$PL(d) = PL(d_0) + 10n\log_{10}\left({d}/{d_0}\right) + S. \qquad (1)$$

$$S \sim N(0, \sigma_s),\ d_0 = 50mm.$$

apparel. In the NIST work, in-body to in-body and in-body to out-of-body propagation effects were treated separately. Their work was adopted by the IEEE 802.15 task group 6 （TG6） on BANs. Therefore, we have applied four NIST channel models in this paper.

TABLE I. NIST CHANNEL MODELS

Implant to Body Surface	***Path Loss (dB)***	***n***	***σ_s (dB)***
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81
Implant to Implant	***Path Loss (dB)***	***n***	***σ_s (dB)***
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05

We evaluated communication performance under different BANs scenarios, as shown in Figure 1. The x-axis is aligned to the human facing direction.

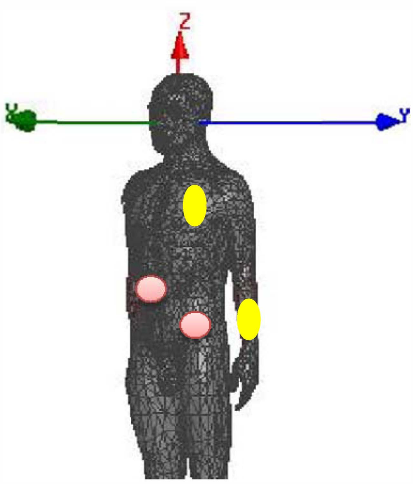


Figure 1. Simulation Scenarios of Different Sensor Nodes Locations.

Two red circles represent body implantable sensors (one is deeply implanted, while the other is implanted near the body surface) placing inside body tissue around the stomach. Two yellow ovals represent body-wearable sensors (one on wrist, the other is above the heart) upon the body surface. Pairwise communication paths are in accordance with Table I.

II. DESIGN OF THE REAL-TIME PLATFORM

In this section we provide an overview of our hardware platform design and some results illustrating the validity of the platform.

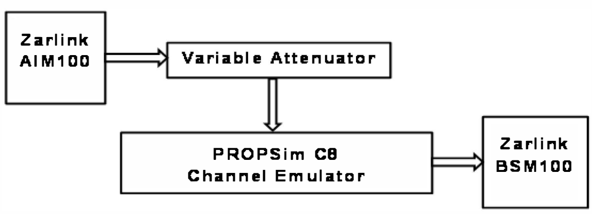


Figure 2. Body Area Network Hardware Platform Block Diagram.

A. Hardware Platform Implementation

We used two major hardware components for our measurements: an Elektrobit PROPSim C8 multipath channel emulator and a Zarlink ZL70101 Application Development Kit. The block diagram is shown in Figure 2. Figure 3 shows the actual hardware setup for our hardware platform.

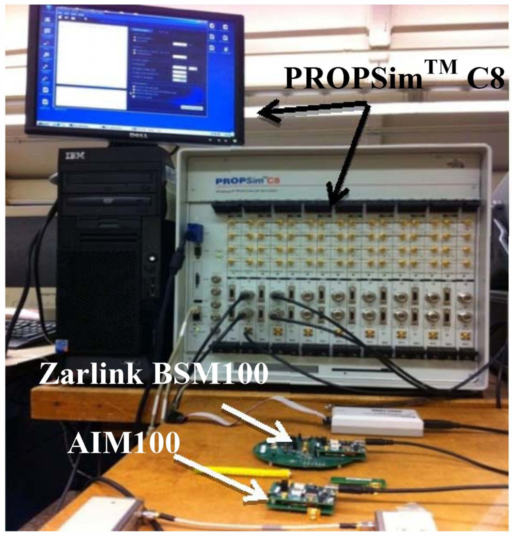


Figure 3. Body Area Network Hardware Platform Set.

The PROPSim C8 emulates eight independent channels between transmitter and receiver. It contains a built-in PC as well as channel emulator, simulation control software. Users are able to customize parameters such as path loss, fading parameters, delay and phases of multipath components. Therefore PROPSim C8 plays an important role in our platform, performing repeatable NIST channel emulation at the 403.5 MHz center frequency.

The Zarlink ZL70101 ADK development system includes Base Station Module (BSM100), Application Implant Module (AIM100) and Programmer Cable Adapter. Both of the two aforesaid medical devices can function as Transmitter and Receiver, designed to operate in the 402-405 MHz Medical Implant Communication Services (MICS) band [12] and the 433-434 MHz Industrial-Scientific-Medical (ISM) band. A Reed-Solomon coding scheme together with CRC error detection were used to provide an very reliable link. Zarlink boards were used as DUT.

Given that Zarlink boards do not necessarily require two-way channels to establish connection, we used only one channel in our platform. Thanks to PROPSim's unidirectional properties, communication is independent and less influenced with no feedbacks, which produces better results. The arrows in Figure 2 indicate the signal flows in our platform.

B. Platform Evaluation

Here we verify the ability of reproducing NIST channel models utilizing our platform. The setup of the channel model consists of two parts: setting the power of the impulses, and choosing the fading model. Therefore, we begin by assessing the RSSI (path loss) accuracy of our platform, and then simulated fading model is compared with NIST channel model.

1) Path Loss Accuracy Verification

A static channel model was first applied in our platform. After varying path loss and recording every corresponding measured RSSI, we graphed the relationship between expected receive signal strength (RSS) and real tested RSSI, as displayed in Figure 4. Zarlink User Manual [5] shows how to convert RSSI to received power in dB (see dashed line). Since static model is used,

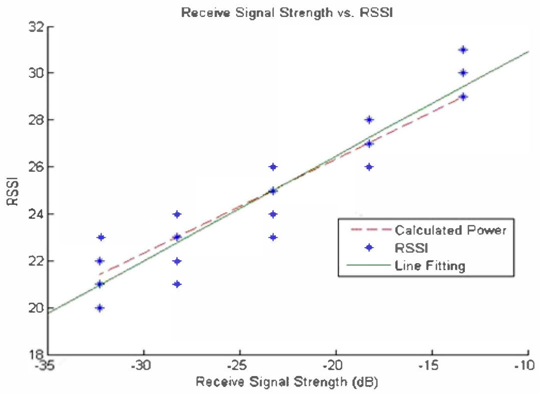
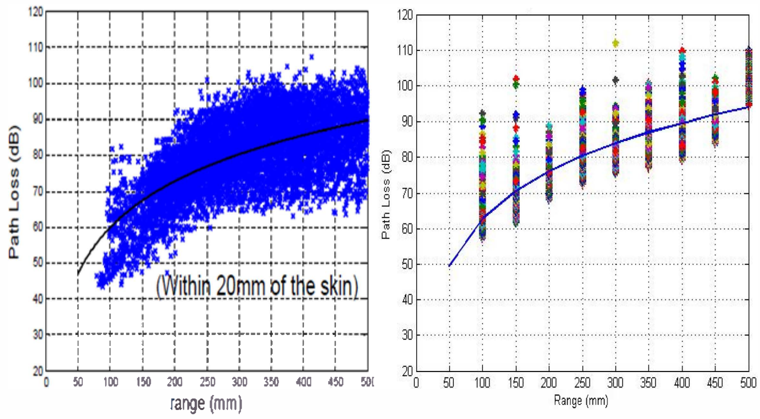


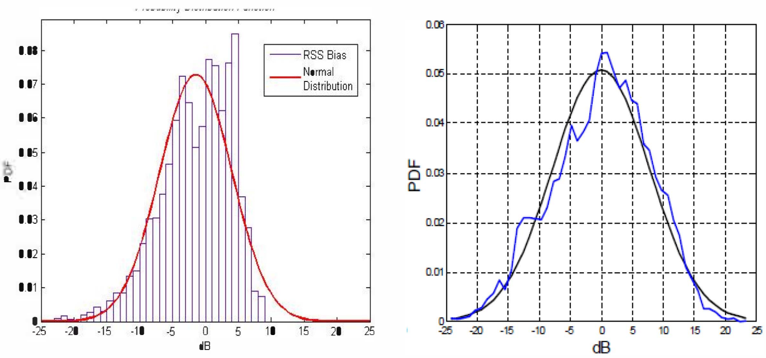
Figure 4. Receive Signal Strength vs. RSSI.

RSSI has small variation. The line fitting curve of our test specimen are shown by the dots and solid line. Although there are still slight differences, we judge that they nearly coincide. Thus we concluded that our platform is sufficiently accurate in path loss aspect.



(a) Simulation (b) NIST

Figure 5. Comparison of Path Loss vs. Distance Scatter Plot Between Our Platform Measurements and NIST Statistical Model.



(a) Simulation (b)NIST

Figure 6. Comparison of Probability Distribution Function Plot Between Our Platform Measurements and NIST Statistical Model.

2) Fading Accuracy Verification

By substituting the Zarlink Implant and Base Station Boards with Network Analyzer (Agilent Technologies E8363B) transmitter and receiver, respectively, simulated channel propagation through platform is observed. Gaussian fading was added in our hardware platform as given in Table I using PROPSim C8. Due to fading effects, path loss varies dramatically at any fixed range. The implant to on-body surface channel model is presented as an example. After collecting more than 500 path loss values at each TX-RX distance, a curve fitting plot of path loss was generated as shown in Figure 5(a). Figure 5(b) is the scatter plot from the NIST results [10].

The Probability Distribution Function (PDF) plot of RSS bias is also presented in our paper. Figure 6(a) is the PDF plot of our practical measured path loss. We can observe from this figure that with normal fitting, the peak is at 0 dB representing zero-mean, ranging from -25 dB to 25 dB, which coincide with NIST's PDF plot in Figure 6(b) [10]. Thus, our fading model is verified. Given that the path loss and fading models are both in accurate, we concluded that we are able to reproduce NIST statistical channel model with our real-time hardware platform for BANs. Consequently, our platform configuration was adopted for the further results introduced in Section IV.

III. REAL-TIME PERFORMANCE EVALUATION

To establish connection, communication is initiated by the Zarlink AIM100 as indicated in Figure 2. The BSM100 works as receiver and counter, in "listening for emergency" state, watching constantly for any output packet from the Implant board. To accurately evaluate link performance, several parameters have to be fixed, such as no retransmission, -1 dB transmit power, and same packet and block length. Every emergency packet includes 31 blocks, and every block contains 3 bytes for the User PID [5].

TABLE II. MODULATION PROPERITES

Channel Modulation	***Raw Data Rate***	***Sensitivity***
2FSK high sensitivity	200 kbps	-81 dBm
2FSK high rate	400 kbps	-76 dBm
4FSK	800 kbps	-70 dBm

In sight of Zarlink system configuration, three different modulations: two kinds of binary FSK (2FSK) at different data rates and 4-ary FSK (4FSK) as shown in Table II are discussed. Simulations were performed at 5 specific TX-RX distances: 50 mm, 100 mm, 150 mm, 200 mm and 250 mm. 20 transmissions were made at each specific TX-RX distance, 1000 packets at a time. Therefore, a total number of up to $20\times1000\times5\times3$=300,000 packets were sent for each of the four channel models.

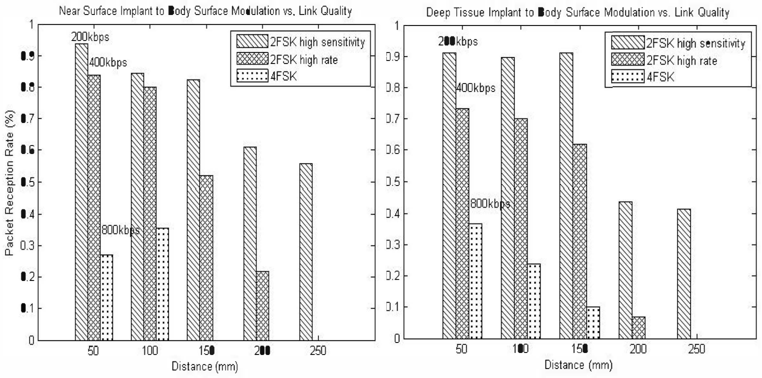
PRR was used as benchmark in this work indicating link quality, which is an important reliability metric for communications. This ratio stands for the number of successfully received packets divided by number of total transmitted packets. The higher PRR achieved, the better the link performed.

Our results for channels through the body and inside the body are displayed separately, in view of differences between through body and in-body propagation characteristics.

A. Implant to Body Surface

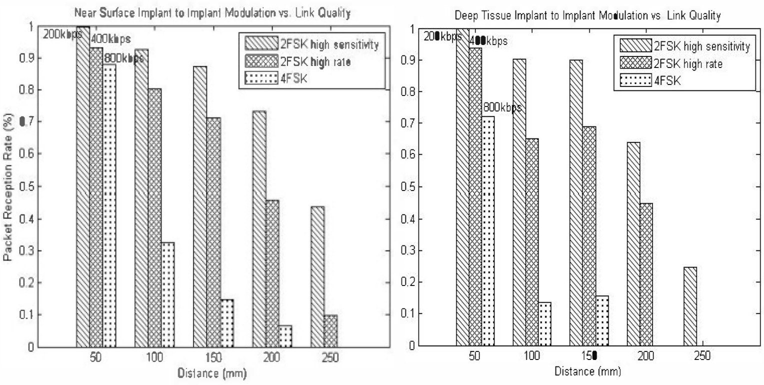
We can observe from Figures 7 (a) and 7 (b) that for any TX-RX distance tested, 2FSK high sensitivity modulation always achieves the best performance. The 2FSK high rate modulation has poorer link quality compared to 2FSK high sensitivity with lower PRR, while 4FSK is the poorest of the three modulations. When distance is greater than 100 mm, BSM100 can hardly maintain connectivity with AIM100 using 4FSK modulation.

B. Implant to Implant



(a) Near Surface Implant (b) Deep Tissue Implant

Figure 7. Implant to Body Surface Modulation vs. Link Quality.



(a) Near Surface Implant (b) Deep Tissue Implant

Figure 8. Implant to Implant Modulation vs. Link Quality.

In Figure 8 (a) and (b), similar results are observed with implant to body surface in Figure 7 (a) and 7 (b), and we can easily judge that 2FSK high sensitivity modulation always outperforms the other two. But in additional, not only the PRR of 2FSK high sensitivity is approaching 100% at 50 mm, 2FSK high rate and 4FSK also attain good performance. Moreover, even 4FSK can reach up to 200 mm, which is significantly better than seen for the implant to body surface case discussed previously. These results indicate that the implant to implant body area communication has better link quality than implant to body surface channel.

CONCLUSION

This paper described a real-time hardware platform for performance evaluation of BANs. The ability of PROPSim C8 to precisely emulate in-body wireless propagation environments has been verified in path loss and fading aspects. Zarlink boards functioned as transmitter and receiver communicating through the PROPSim C8 emulator, providing valuable insight into how BANs will perform in communications with medical implants. This emulation platform approach can be very estimable in facilitating BANs link performance assessments prior to implanting devices inside a patient's body.

Hardware platform explored the relationship between modulation selection and link performance. It shows 2FSK high sensitivity modulation has the highest PRR, i.e. better performance for the MICS band. Moreover, implant to implant channels exhibit better link quality than do implant to body surface channels. The results discussed multiple aspects which are satisfactory and desirable. Along with the repeatable, multipath and real-time properties, our hardware platform can be used extensively for various body area network scenario channel propagation models evaluation. It also helps test and understand practical performance of medical devices implemented inside human body. With broad application foreground, our hardware platform can be utilized on other objectives, such as in-body localization, in future.

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