A Virtual Reality Platform to Study RF Propagation in Body Area Networks

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Abstract **—In-depth understanding of the propagation media is essential for the design of efficient wireless communication protocols for body area networks. Obtaining sufficient amount of data for different scenarios via physical experiment is either difficult or in the case of implant communication, nearly impossible. Therefore, a detailed 3D virtual reality platform can be extremely useful in highlighting the RF propagation characteristics inside and around the human body. Such a platform provides necessary insight into radio wave propagation for body area networks. It can also be used to identify the best scenarios for limited physical experimentation and measurements. In this paper, a virtual reality platform that gives us the ability to observe three-dimensional RF propagation from implantable and wearable sensors is presented.. We have used this virtual environment as a scientific instrument to study various Radio Frequency communication channels inside or on the surface of a human body.**

Keywords – 3D virtual reality platform; Body Area Networks; Radio frequency propagation

I. INTRODUCTION

A Body Area Network (BAN) is a radio communication protocol for short range, low power and highly reliable wireless communication for use in close proximity to, or inside, of a human body. It includes Radio Frequency (RF) enabled nodes that could be implanted, worn or located adjacent to the body. BAN is poised to be a promising interdisciplinary technology with novel uses in pervasive health information technology. There are still numerous technical, commercial and regulatory challenges facing this technology. For example, usability, interoperability, energy source, miniaturization, less intrusive sensing/actuation technology, security and privacy are among these challenges [4]. An attractive set of applications such as electrocardiogram (ECG), temperature, respiration, heart rate, blood pressure and pH monitoring can be offered by radio-enabled wearable medical sensors. Similarly, novel applications such as smart pills for precision drug delivery, glucose monitors, blood pressure sensing system, and eye pressure sensors for glaucoma patients can become reality using wirelessly controlled implantable sensor nodes [5].

Considering the recent advances in microelectronics, the technology to build very small and extremely low power wearable devices is clearly within our reach. Commercial success of these devices strongly depends on the adoption of a global standard for their communication channel (i.e., air interface). Other factors such as co-existence with other wireless technologies, worldwide availability of the frequency spectrum (e.g. regulatory issues) and also the capability to have appropriately sized antennas determine the choice of the radio frequency for use in body area network applications.

Design of efficient transceivers for body area networks requires in-depth knowledge and understanding of the propagation media (i.e. human body). Obtaining sufficient amount of data for various scenarios is very difficult for wearable nodes. Also, this is almost impossible for implanted devices due to the difficulties of performing physical experiments with human subjects. Therefore, a 3D virtual reality platform that can emulate physical measurement can be extremely beneficial in understanding and highlighting the RF propagation behavior in BANs. Although, verification with physical experiment is ultimately needed to investigate the reliability of the results, such virtual environments could also be used to determine the best (i.e. optimized) test scenarios for limited physical measurements.

On the other hand, the results of several experiments reported in the literature [9], have led to varying conclusions in the statistical parameters of a propagation model for body area networks. These discrepancies are usually due to variations in the exact scenarios (i.e. node locations, body posture, etc.), the surrounding environments where the actual measurements took place and most importantly the antennas used across different experiments. These results simply point to the need for more detailed studies to understand the behavior of radio frequency waves over the human body surface. In [9], we have explained how an extensive simulation platform can be used to better understand the discrepancies between various sets of physical measurements related to body surface propagation.

In the following sections, we present such a virtual reality platform and describe how it can be used to study RF propagation and extract various channel modeling parameters in body area networks. The rest of this paper is organized as follows. Section 2 will describe the block diagram and functionality of the 3D virtual reality platform that we have constructed to study RF propagation in BANs. Section 3 discusses the complexity of BAN antennas and provides examples used in some of our simulations. Then, a few applications of this virtual platform in studying RF propagation in BANs are provided in Section 4. Finally, concluding remarks and future plans are presented in Section 5.

II. A VIRTUAL REALITY PLTFORM FOR BODY AREA NETWORKS

Inhomogeneity and complexity of the propagation medium along with possible propagation paths from any direction necessitate a 3D environment to better capture, visualize, and understand RF propagation from/to implants or wearable body sensors. The complexity of the propagation environment surrounding a medical implant would also imply that an appropriately designed immersive platform would be very helpful in better understanding the radio frequency channel characteristics inside the human body. Lack of a detailed human body model and realistic wearable/implantable antennas are usually among the shortcomings of previous simulation studies in this area. In addition, an immersive environment that allows 3D data visualization and interaction with the objects under study will undoubtedly be very helpful in understanding complicated phenomena associated to human body RF propagation.

The block diagram of our virtual reality platform is shown in Fig, 1. The main components of this system are: a three-dimensional human body model, the 3D immersive & visualization platform, the propagation engine (i.e., HFSS[1], three-dimensional full-wave electromagnetic field simulator), and finally virtual models of the BAN antenna. The three-dimensional human body model has a resolution of 2 mm. It includes frequency-dependent dielectric properties of 300+ parts of a male human body. These dielectric properties are user-definable in case custom modifications or changes are desired.

The 3D immersive platform as shown in Fig. 2 includes several components: a visual display consisting of three large screens, stereoscopic glasses that are motion-tracked, and an input device that is also motion-tracked. The three large video projection screens are arranged edge-to-edge in a corner configuration; these are used as a single 3D stereo display. The 3D scene is updated for the position of the stereo glasses given by the motion tracker. This enables the immersive platform to present a virtual 3D world within which the user can move and interact with the virtual objects. A hand-held three button motion-tracked wand with a joystick is the principal interaction device.

Such immersive platforms are usually used to provide a qualitative display of data. Researchers navigate through the data representations, change orientation and scale, and manipulate the components of the scene with a variety of interaction techniques. This enables the scientist to perform qualitative assessments of their data such as seeing spatial relationships among the data objects and looking for patterns; this is typically how virtual reality platforms are used for visualizing scientific data. Applications such as architectural walk-throughs [10] and psychological treatment [11] are clearly being used to provide the user with a qualitative subjective experience.

Our immersive platform has been used in applications such as chemical simulations, microscopy, and rheological properties of concrete [1,2]. But we have extended the qualitative uses of the system by adding quantitative analysis tools for various applications [1,12]. We have implemented several such quantitative tools which are described below. It is our intent that these quantitative tools enable our immersive visualization and analysis system to become an integral part of the research effort.

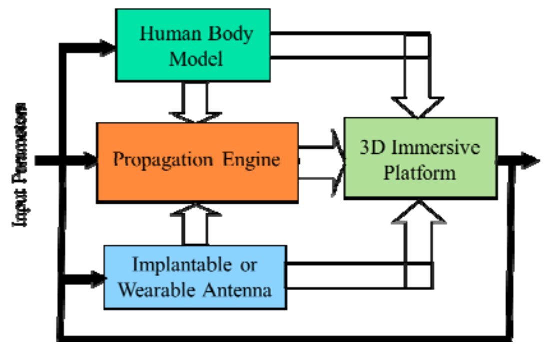

Figure 1. System block diagram

The last component of the immersive system is a virtual body wearable or implantable antenna that has been carefully designed for the target application. The operating environment for a BAN device is quite different from the traditional free space communication. Reliable network operation requires efficient design of the antenna for the wearable or implantable device. The dimension of the antenna (especially for implant applications) must be very small. This creates efficiency issues at low frequencies. The implant antenna should also be biocompatible for health and safety issues.

Input parameters to the above virtual reality system includes all antenna attributes such as position, orientation, operating frequency, transmit power, as well as resolution, range and the choice of the desired output parameters. The HFSS propagation engine in this system enables the user to calculate a variety of different electromagnetic quantities; examples of which are magnitude of magnetic/electric fields, Poynting vectors, Specific Absorption Rate (SAR), etc.

In this environment, a researcher can place a custom designed antenna at the desired location of the human body; set the operating frequency of the node; and, study the RF propagation at any location inside or around the body. The

[1] HFSS is registered trademark of ANSYS Corporation. The HFSS has been used in this research to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standard and Technology, nor does it imply that this product is necessarily the best available for the purpose.

platform user can observe the data representations at his desired scale and position. He can physically move through data, and change visual orientation. He can also control the elements of the virtual world using a variety of interactive measurement and analysis techniques. All of these capabilities are especially useful for the 3D study of RF propagation to/from implanted or wearable body devices. In addition, a more convenient and natural interaction between experts with different backgrounds would be possible using this system. For example, a surgeon can point to the exact location of an implant using the interactive tools; and then, an antenna designer can design the antenna to fit the chosen location given the physical and biological constraints. An RF engineer, in turn, would be able to observe the propagation performance for the target communication link or compute other measures such as SAR given the transmitted power.

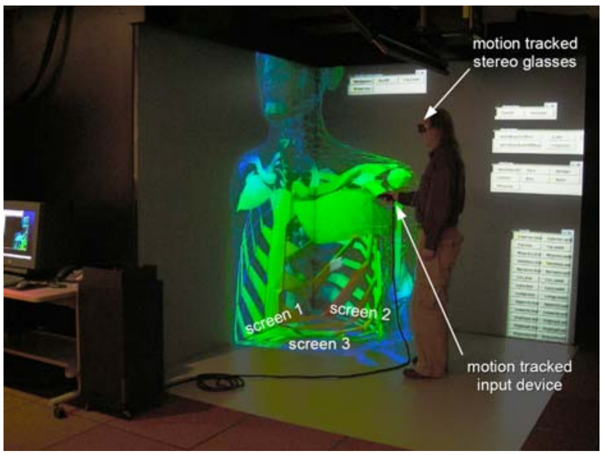

Figure 2. NIST Virtual Reality Environment

III. CHALLENGES IN BAN ANTENNA DESIGN

Another key component in wireless body area network is the antenna. Designing appropriate antennas for BANs is much more challenging compared to other wireless systems that operate in their natural environments. Among these design challenges, we can point to form factor and size-limitation, bandwidth, efficiency and gain within the limited antenna volume. The influence of the human body on the antenna characteristics (e.g. gain pattern distortion) has to be carefully considered during the design phase. Otherwise, central frequency shift as well as pattern fragmentation will degrade the performance of the antenna in practice [6,7].

For wearable BAN sensors, Ultra Wide-Band (UWB) seems to be a favorable technology. Low power consumption (due to less complexity in their transceiver), possibility to have small-sized antennas along with worldwide spectrum availability are among the reasons for this choice. Fig. 3 shows an example of a loop antenna that has been carefully designed for body surface communication. The operating frequency range of this antenna is 3.1-5.1 GHz and its dimensions are 29.25×38.5×1 mm. It includes a side of FR4 substrate with dielectric constant of $\varepsilon_r = 4.4$ and loss tangent of $tan\theta = 0.02$. The VSWR (Voltage Standing Wave Ratio) of this antenna in proximity to the body surface is shown in Fig. 4. Further study of the performance of this antenna in free space and in direct contact with the human body can be found in [3,4].

An example of an implant antenna is shown in Fig. 5. This antenna can be used for applications such as pacemaker or ICD. It consists of a single metallic layer printed on a side of a D51(NTK) substrate with dielectric constant of $\varepsilon_r = 30$, loss tangent of $\tan\theta = 0.000038$, and thickness of 1 mm. The metallic layer is covered by RH-5 substrate with dielectric constant of $\varepsilon_r = 1.0006$, loss tangent of $\tan\theta = 0$, and thickness of 1 mm. The antenna dimensions are 8.2 x 8.1 x 1 mm. This makes it quite appropriate for some medical applications. The simulated return loss of this antenna is shown in Fig. 6. As observed, it provides great impedance matching in the Medical Implant Communication Service (MICS) frequency band (i.e. 402-405 MHz). More information on the performance and design of this antenna has been provided in [14,15].

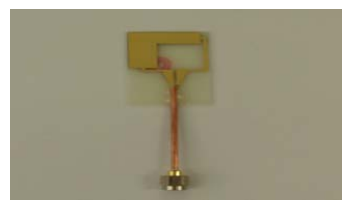

Figure 3. The UWB Antenna

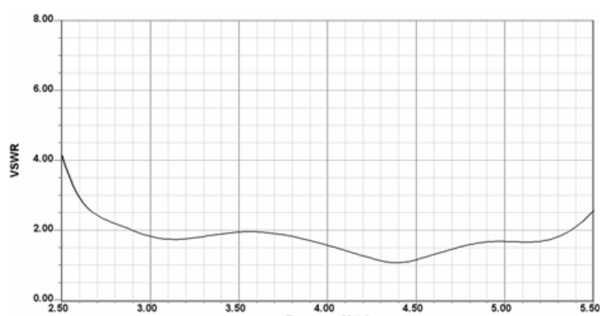

Figure 4. Antenna VSWR on the body surface

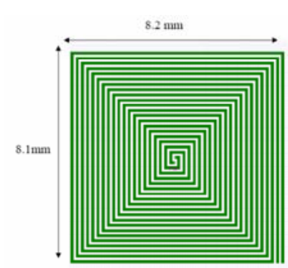

Figure 5. Front view of the implant antenna

IV. RF PROPAGATION RESEARCH USING THE VIRTUAL REALITY PLATFORM

The virtual reality platform discussed in the previous sections is a powerful tool to study various RF propagation characteristics inside and on the surface of the human body. In this section, we briefly point to some of the capabilities of this platform and highlight sample research results that can be obtained through extensive simulation.

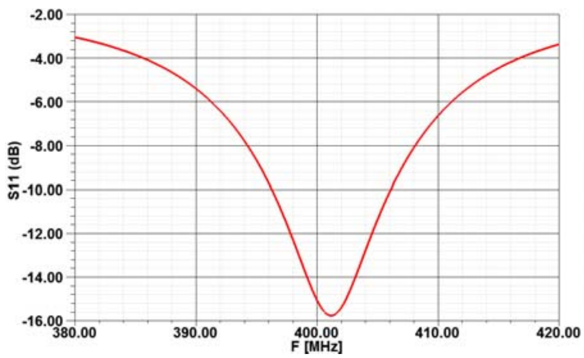

Figure 6. Implant antenna (Return Loss)

As mentioned in Section III, the antenna is an essential component of body area networks and has to be carefully designed given the intended application. Unlike other applications, the design process for a BAN antenna has to consider the environment where it is supposed to operate. The virtual reality platform is an ideal environment to evaluate the performance of such antennas. We have developed tools to visualize the 3D antenna gain patterns in any direction and distance. Figures 7 and 8 demonstrate virtual planes that can be controlled by the user and show the signal intensity (i.e. proportional to gain) from the antenna. The antenna is shown by the gray square located on the chest as observed in Fig. 7. The figures also highlight the body surface signal intensity at the same time. Using such tools, an antenna designer can visually observe how much of the signal energy is propagated off-body and how much is directed on the body surface. This is an important issue as the particular application could require different antenna design for off-body versus body-surface communication. The antenna designer can immediately evaluate how the antenna performs on off-body versus body-surface links.

A very interesting phenomenon in body surface propagation is the existence of surface diffracted creeping waves. This phenomenon greatly impacts the fading characteristics of radio waves for on-body communication. Visualization of such creeping waves would be a very helpful insight and could allow the antenna designer to exploit this characteristic for more efficient designs.

During a virtual experiment to study path-loss from medical implants, we noticed the existence of this phenomenon by visualizing the Poynting vector direction along the body surface. The Poynting vector is a quantity that is proportional to the cross product of electric and magnetic fields. It describes the magnitude and direction of the flow of energy in electromagnetic waves. The small vectors on the body surface shown in Fig. 9 represent the Poynting vector direction and its magnitude. Although, in this case, the implant was located in the stomach area, a strong surface creeping wave was observed over the body surface.

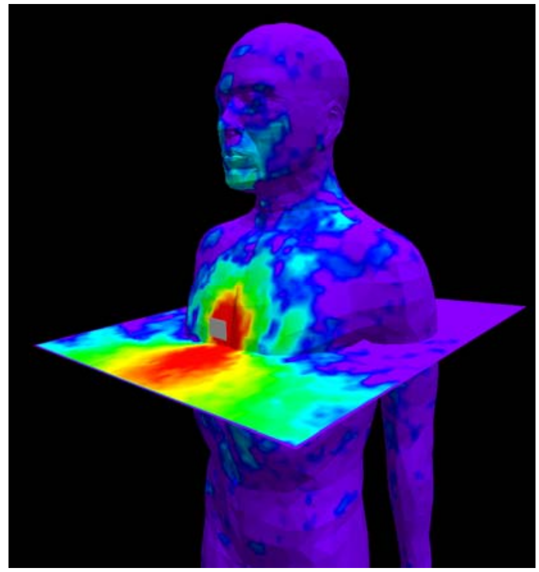

Figure 7. Horizontal view of off-body and on-body signal intesity

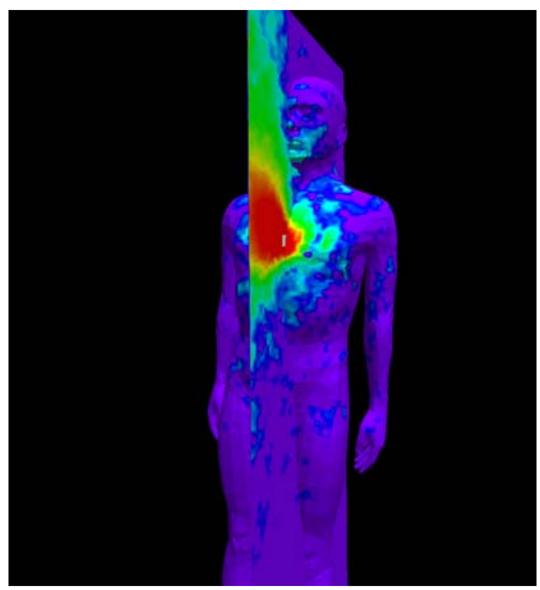

Figure 8. Vertical view of off-body and on-body signal intensity

To study this phenomenon more closely, we set up more virtual experiments with a body surface antenna that is located on the surface of the body around the stomach area. With creeping waves the direction of the Poynting vector will be parallel to the surface on which the wave is propagating. Therefore, using the virtual reality platform, we developed tools to further observe this property, and circumstances under which it occurs. These tools involve geometrical and computational techniques to calculate the direction of the Poynting vector with respect to the body surface at a given distance away from the body.

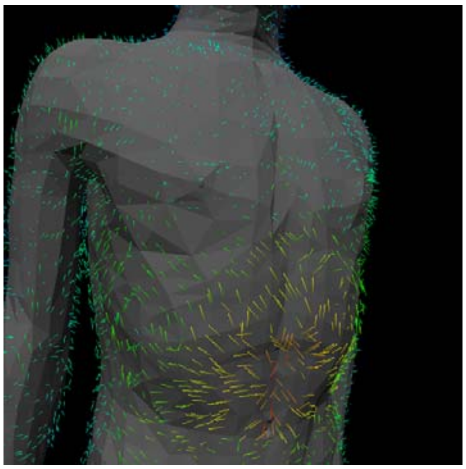

Figure 9. Poynting vector direction on the body surface

Figure 10 displays the results of the study mentioned above. The red colors are indicative of high degree of parallelism, followed by green representing less parallelism and then blue with the least parallel Poynting vectors. The left image in Fig. 10 only includes Poynting vectors that are within 1cm of the body surface while the right image corresponds to a distance of 3-4cm. Although the antenna is located on the stomach, a high density of red colors are observed on the chest, shoulders, thighs and even legs for the 0-1cm case. This shows a strong creeping wave existence within 1cm of the body surface. As the distance from the body increases, the occurrence of this phenomenon becomes less. The right-side image in Fig. 10 demonstrates a very low density of red colors i.e. no creeping waves at 3-4 centimeters from the body surface. Several recent results in the literature have indicated a path-loss exponent of less than 2 (i.e. better than free space) for on-body communication [13]. The creeping wave phenomenon could explain the reason for such low path-loss exponents in body-surface communication as observed by our virtual reality platform. This also aligns with the results of our path-loss modeling effort for UWB frequencies as discussed in [9].

Although the qualitative usage of our virtual reality platform can be extremely helpful in understanding complex electromagnetic waves behavior in body area networks, it can also be used for several important quantitative studies [8]. For example, various data such as signal intensity, antenna radiation pattern and SAR can also be estimated by performing interactive virtual experiments. Figure 11 displays the capability of the platform to calculate signal intensity profile along a line that was interactively specified connecting two arbitrary points which could be located inside, on the surface, or in the vicinity of the body. We have omitted the discussion of these capabilities in this article for brevity.

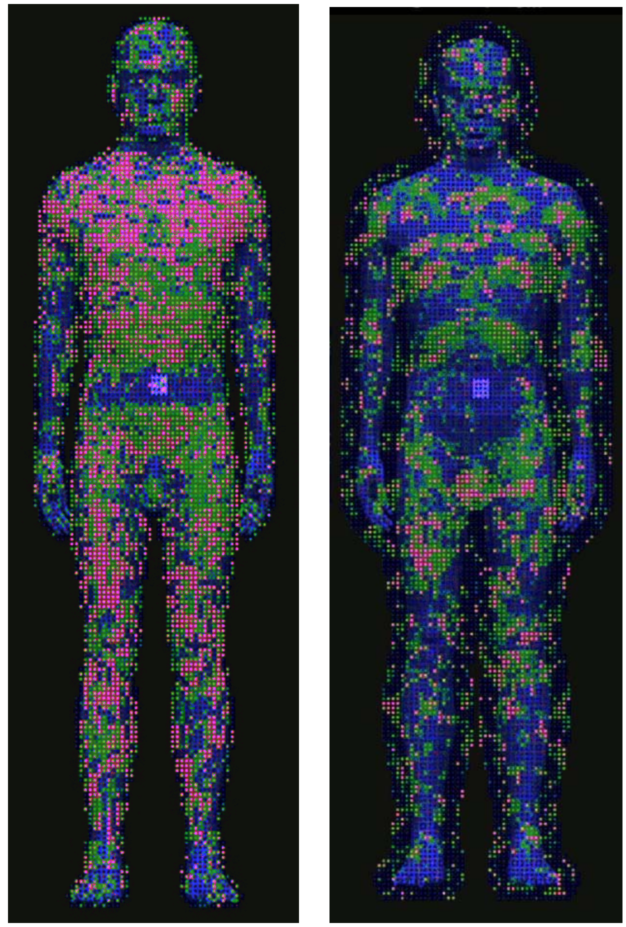

Figure 10. Visualization of Creeping Waves: Left: 0-1 cm distance from body surface; Right: 3-4 cm from body surface

V. CONCLUSION

Our 3D virtual reality platform with its quantitative features is a powerful tool that enables extensive research in the cross-disciplinary field of body area networking. As mentioned, evaluating the efficiency of custom made antennas and studying the creeping wave propagation on the body surface can be easily done in our system.

In addition to qualitative and quantitative data observation and statistical processing, studying RF propagation for specific medical applications such as cochlear implants, brain neural interface and retina implants is also possible using such platforms. Also, methodologies to generate personal 3D body models based on MRI imaging can be used to study impact of various body-postures on RF propagation inside the human body. Additionally, custom body models for people carrying artificial organs can be generated in order to investigate the possible effect of the change in dielectric parameters on RF propagation. This can also be extended to include propagation study for wearable RF-enabled textile in BAN applications.

In a body area network, the communication path with an implantable or wearable node could be through any direction inside, over the surface or outside of the human body; therefore, a true three-dimensional environment is required to completely visualize and understand RF propagation from such devices. As various body motions and postures complicate this issue even further, a dynamic virtual environment capable of reflecting real-time body motion would be highly desirable for future research.

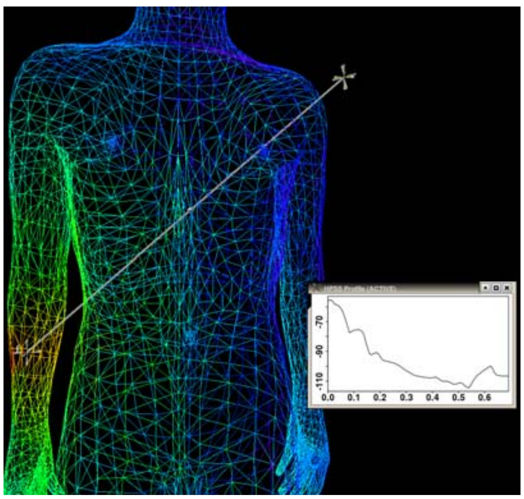

Figure 11. Signal intensity along a line

The authors hope that the virtual reality environment introduced here would create a flexible and general purpose platform to visualize and understand BAN propagation. More in-depth research on this subject along with physical measurement validation is undoubtedly required to further understand the characteristics of radio frequency propagation in body area networks.

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