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SAR and BER Evaluation Using a Simulation Test Bench for *In Vivo* Communication at 2.4 GHz

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***Abstract*—We present a simulation method and results that utilizes accurate electromagnetic field simulations to study the maximum allowable transmitted power levels from *in vivo* devices to achieve a required bit error rates (BER) at the external node (receiver) while maintaining the specific absorption rate (SAR) under a required threshold. The BER of the communication can be calculated using the derived power threshold for a given modulation scheme. These results can be used to optimize the transmitted power levels while assuring that the safety guidelines in terms of the resulting SAR of transmitters placed in any location inside the human body are met. To evaluate the SAR and BER, a software-based test bench that allows an easy way to implement field solver solutions directly into system simulations was developed. To demonstrate the software-based test bench design, a complete OFDM-based communication (IEEE 802.11g) for the *in vivo* environment was simulated. Results showed that for cases when noise levels increase or the BER becomes more stringent, a relay network or the use of multiple receive antennas, such as in a MIMO system, will be become necessary to achieve high data rate communication.**

Keywords-SAR; BER; in vivo propagation; medical implants; wireless communication.

I. INTRODUCTION

Wireless communication for biomedical applications is a research topic that has seen a tremendous increase in attention in recent years [1]–[6]. Implanted sensors and actuators for medical applications have the potential of being critical components in advanced health care delivery by reducing the invasiveness of a number of medical procedures. Such applications include, but are not limited to, internal health monitoring and drug administration [7], [8]. Therefore, wireless communication between *in vivo* sensors/actuators and *ex vivo* transceivers will play a crucial role in advancing minimally invasive health care delivery.

There is also interest in developing high date rate communication systems between implanted and external transceivers for minimally invasive surgery. For example, one application that would require high data transmission capabilities is high definition (HD) video from *in vivo* camera modules.

To reliably transmit a high data rate signal through the *in vivo* channel requires a given SNR and appropriate forward error control. One method to monitor the performance of a digital communication system is to measure the bit-error-rate (BER) of the communication. A low BER is needed for high communication performance which depends on the transmission power to obtain the required SNR. But since we are transmitting through or near the human body, the signal levels are limited to the safety guidelines set by the Federal Communications Commission (FCC).

SAR levels of radiofrequency (RF) radiation produced by cellular phone activity near the human head have already been extensively investigated [9]–[11]. SAR effects near other parts of the human body, such as in body area networks (BAN) applications [12] have also seen increased attention [13]. However, to the best of our knowledge, research in SAR levels produced by *in vivo* devices has so far been very limited [14]. Although, in [14], the authors provided results for SAR and BER evaluation for implant BAN's operating at the 400 MHz ISM band. But due to an increasing need to provide high data rate in *in vivo* communications, it is essential to evaluate the SAR under BER requirements at higher frequencies. Such results will give the system designer guidance about whether a relay network will be needed to attain reliable communications through the extremely lossy and dispersive *in vivo* channel [15].

In this paper, we calculate the SAR levels and communication BER using a software-based test bench, where the system designer can easily monitor the performance of the communication while, at the same time, observing the SAR levels in highly accurate *in vivo* environments. We utilize the dynamic link capabilities between the ANSYS Designer, which is a complete RF circuit and systems simulation tool, and ANSYS HFSS, a high frequency numerical electromagnetic field simulator, along with a highly accurate human body model in HFSS, to create the test bench.

In section II, we describe the SAR and its influence in the BER. A detailed description of our software-based test bench is presented in section III. In section IV, we give an example of a complete communications system and show the derived BER as a function of transmission power levels and the resulting SAR levels as measured numerically in HFSS. In section V, we present our conclusions.

II. SAR AND BER

The interaction of electromagnetic fields with human body tissues cause localized tissue heating and damage in the vicinity of radiating sources at unsafe power levels. To restrict the amount of radiation that the living tissue can be subjected to, strict guidelines were set by the FCC. The SAR, a measurement of how much power is absorbed per unit mass of a conductive material, is defined as [16]:

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$$SAR = \frac{\sigma|E|^2}{\rho} \tag{1}$$

where σ is the electrical conductivity of the material, E is the RMS magnitude of the electric field at a given point and ρ is the mass density of the material. The FCC recommended that the SAR level is given for localized areas over any 1 gram of tissue and for values averaged over the whole human body, also known as local SAR and average SAR, respectively. The limit for the local SAR and average SAR are 1.6 W/kg and 0.08 W/kg, respectively.

Since the communication system is limited by how much wireless power can be transmitted near and through the human body, emphasis is placed on optimizing the system performance to assure that the required BER for reliable wireless *in vivo* communication is met. The test bench presented in this paper uses a propagation channel model derived directly in HFSS, meaning that the BER values in each simulation are dependent on the specific antenna performance and placement. Therefore, this test bench allows the system designer not only to decide on optimum system architecture and data rates for reliable communication, but also the flexibility of using different antenna architectures whereby also optimizing the antenna designs and placement. With this test bench, *in vivo* devices can be arbitrarily placed in any part of the human body and easily characterized for SAR levels and BER.

III. TEST BENCH

The test bench presented in this paper was implemented in ANSYS Designer 8.0 [17] and HFSS 15.0 [18]. Designer allows for complete communication systems design, both at the system and circuit levels. For digital systems, link quality measurements such as BER, constellation diagrams, eye diagrams, among others, are easily simulated in Designer. ANSYS also provides a complete human body model of a detailed adult male with over 300 muscles, organs, and bones with a geometrical accuracy of 1 mm with realistic frequency dependent material parameters (conductivity and permittivity) from 20 Hz to 20 GHz. This model is used in HFSS to derive the complete electromagnetic fields produced by an arbitrary radiation source, from which other characteristics, such as scattering parameters and SAR levels can be directly obtained.

The simulation steps are as follows:

1. The transmit and receive antennas are placed with the human body model into the HFSS design.
2. Field solutions and S-parameter calculations are derived in HFSS over the desired frequency band (and bandwidth).
3. The maximum local SAR levels from the transmit antenna are evaluated in HFSS as a function of frequency. From these data, the maximum allowable power levels can be derived and used in the Designer system simulations.
4. The communication system is set up in Designer.
5. The wireless channel model, derived in the previous HFSS simulation, is used in the Designer system simulations through the direct link between HFSS and Designer.
6. A BER calculation is performed in Designer at various noise levels, using the required power levels (derived in step 3).

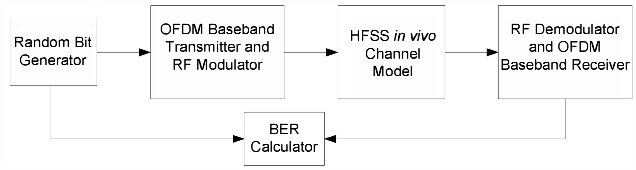

Figure 1. Bock diagram of system level simulation showing direct link to the HFSS *in vivo* channel model.

IV. SIMULATION EXAMPLE

To evaluate the BER performance of *in vivo*, we set up an OFDM-based (802.11g) wireless transceiver model operating at 2.4 GHz with varying transmission and noise power levels, and bit rates in Designer. The system block diagram is shown in Fig. 1.

For simplicity in this proof-of-concept demonstration, monopole antennas were used in the HFSS simulation, which have been optimized to operate at the design frequency. The *in vivo* antenna is placed inside the abdomen to simulate placement of transceivers in laparoscopic and intestinal medical applications and the *ex vivo* antenna is placed at a distance between 1 and 10 cm in front of the abdomen at the same planar height as the *in vivo* antenna to obtain the path loss as a function of distance (the *in vivo* antenna is located 7.8 cm from the abdominal wall). The 3D model used in HFSS showing the antenna locations is shown in Fig. 2.

For this example, only the local SAR values were calculated since the induced SAR levels are mainly localized near the transmitting antenna [9]. HFSS calculates the local SAR levels through the whole body and the test bench provides the maximum value with respect to the input power specified in the system simulation.

Table I shows the calculated SAR levels over the required bandwidth for the 2.4125 GHz 802.11g carrier frequency band with 1mW of transmit power. Since the SAR scales linearly with power, the maximum allowable transmit power can be calculated; 0.412 mW of peak power in this example. The new SAR levels due to the calculated threshold power are also shown in Table I.

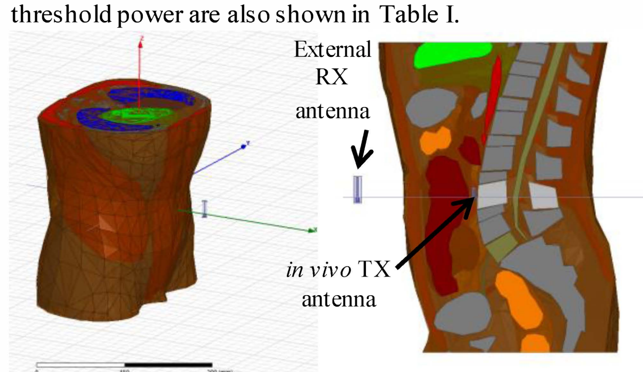

Figure 2. Truncated HFSS human body model used to derive SAR levels and channel model (left). Cross section of same model showing receive and transmit antenna locations (right).

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TABLE I. CALCULATED SAR LEVELS FOR DIFFERENT FREQUENCIES IN THE 2.4 GHZ BAND AT 1MW AND AT THE THRSHOLD POWER.

Frequency GHz	**SAR @ 1.0 mW W/kg**	**SAR @ Threshold Power (0.412 mW) W/kg**
2.402	4.34	1.585
2.412	3.25	1.562
2.422	3.29	1.539

A visual plot of the total SAR levels is shown in Fig. 3. The figure shows the SAR over a cross-sectional cut when viewed from the front and side. From these SAR plot, the location of the maximum total SAR generated at 2.412 GHz occurs at points closest to the *in vivo* monopole antenna. But it can also be observed that the SAR reduces very rapidly away from the antenna, which is to be expected since the electric field attenuates with distance in a conductive medium.

We also calculated the average SAR using the threshold power levels calculated from the maximum local SAR. To calculate the average SAR, we placed a 1 cm^2 averaging box at the location of the maximum SAR. The maximum average SAR was determined in this averaging box and found to be 0.0133 W/kg. This value is within the guideline level of 0.08 W/kg set for the average SAR in the human body.

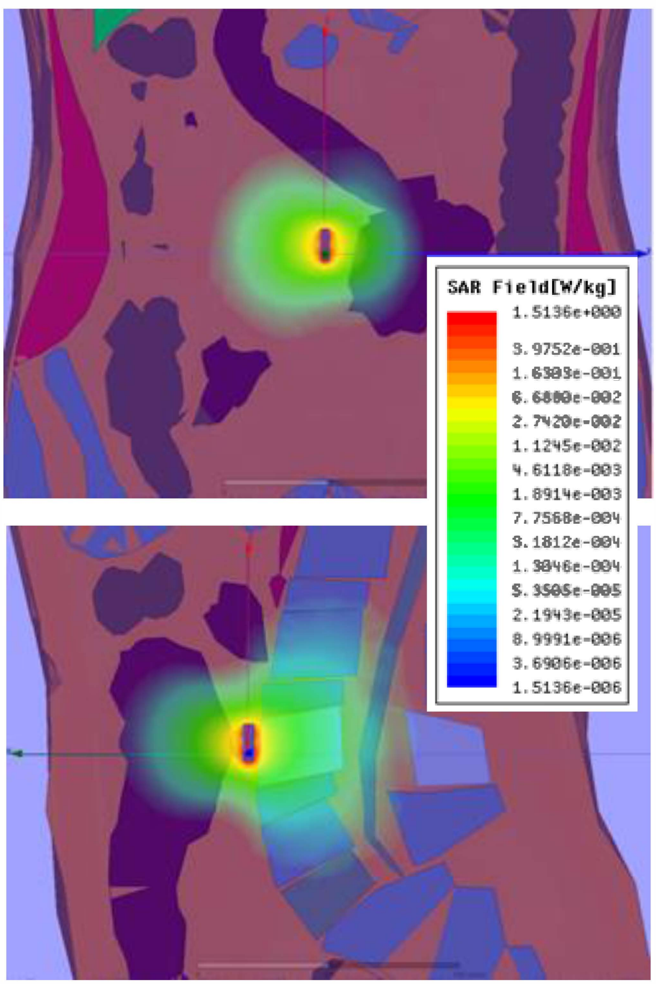

Figure 3. Front (top) and Side (top) cross-sectional views of the total SAR generated at 2.412 GHz inside the abdomen at a transmit power of 0.412 mW.

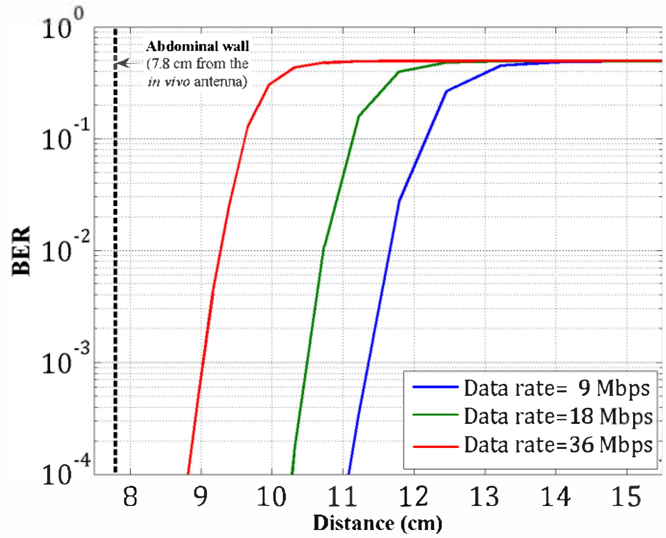

Figure 4. BER performance as function of distance for different data rates at the threshold power (0.412 mW).

The maximum allowable power derived in the HFSS simulation was then used in the OFDM system simulation in Designer. Using a noise level of -101 dBm, the thermal noise with 20 MHz BW, Fig. 4 shows the BER as a function of distance between the external and *in vivo* antenna with added Gaussian noise for three data rates that follow the 802.11g standard for coding rates and modulation types: 9, 18, and 36 Mbps. In the case when transmitting data at 36 Mbps, the external antenna needs to be placed within 1.4 cm from the body to achieve a minimum BER of 10^{-3}.

We also calculated the maximum achievable distance between transmit and receive antennas as a function of the given data rates in the IEEE 802.11g, shown in Fig. 5. The calculation was performed using the maximum threshold power levels of 0.412 mW and a -101 dBm noise level at a BER of 10^{-6}.

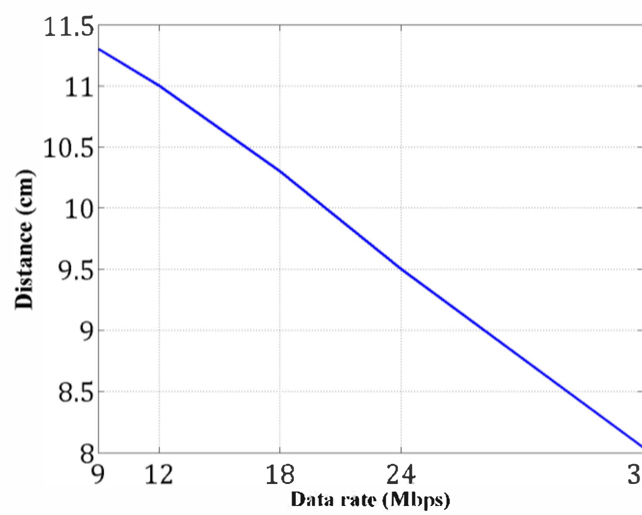

Figure 5. Achievable distance, as a function of bit rate, between *in vivo* and external antennas for a BER of 10^{-6}.

V. SUMMARY

In this paper, we present a simulation method and results that utilizes accurate electromagnetic field simulations, using a software based test bench, to study the maximum allowable transmitted power levels from *in vivo* devices to achieve a required bit error rates (BER) at the *ex vivo* node (receiver) while maintaining the specific absorption rate (SAR) under a required threshold.

Using the simulation test bench, we simulated a complete 802.11g OFDM transceiver using the field simulations obtained from HFSS simulation with the ANSYS human body model from which we found the maximum allowable local SAR and the path loss as a function external receiver antenna location. The threshold power derived from these SAR levels was then used in the system simulation to calculate the corresponding BER as a function of external antenna location for data rates of 9, 18, and 36 Mbps.

From the preliminary data found in this study, it is evident that there are limitations when transmitting at high frequencies from *in vivo* devices to *ex vivo* transceivers while still achieving reliable data transmission, since the maximum transmit power is restricted by SAR safety guidelines. Even when operating under very low noise conditions with moderate BER requirements (10^{-3}), reliable data transmission to an external receiver can only be achieved when located very close to the body. But for cases when noise levels increase or the BER becomes more stringent, a relay network or the use of multiple receive antennas, such as in a SIMO system, will be become essential to achieve high data rates.

We also observed from the simulations that the maximum SAR levels occur at points closest to the transmit antenna from which we can conclude that by placing the transmitter further from organs, the power levels could possibly be increased to obtain higher signal levels at the external receiver. In this example, the transmitter was located very close to the small intestine and the spine. Therefore higher BER should be achievable with proper placement of the *in vivo* transmitter (furthest possible distance from organs and tissues).

The test bench can be used to further optimize the system design (e.g. using asymmetrical OFDM, MIMO transceivers, etc.) as well as the antenna architectures and location to meet BER requirements while always staying within the radiation safety guidelines.

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