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Radiation Characterization of an Intra-Oral Wireless Device at Multiple ISM Bands: 433 MHz, 915 MHz, and 2.42 GHz

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Abstract

Intra-oral wireless devices are becoming more popular for physiological monitoring of the mouth environment and tongue-operated assistive technologies, such as the internal Tongue Drive System (iTDS). Here we present the experimental measurements and simulations of radiation performance of three commercial wireless transmitters operating at 433 MHz, 915 MHz, and 2.42 GHz, in the industrial-scientific-medical band when they were placed inside human mouth. The measurement and simulation results showed similarities in the attenuation patterns of all tested devices and indicated that the maximum attenuation occurs on the back of the head. There were no significant difference of average attenuation pattern between 433 MHz and 915 MHz, while the attenuation of 2.42 GHz was higher in simulations but not in the measurements.

I. Introduction

Recent advances in sensors, wireless communications, and computing have made the development of small wireless intra-oral medical devices feasible and popular. Intra-oral devices can be used for in-mouth physiological environment monitoring and modulation [1], [2]. There is also a group of intra-oral devices under development to work as tongue-operated assistive technologies for people with severe disabilities by taking advantage of the amazing capabilities of the tongue in these individuals [3]–[6].

Both applications require highly efficient and reliable wireless links to transmit parameters measured inside the mouth, such as temperature, pH, magnetic field density, and tongue position, to an external base station for recording and further processing. There have been several studies on characterization of radio propagation around implantable and ingestible wireless devices. Scanlon et al. numerically and experimentally characterized a vaginal implant at 418 and 916 MHz [7]. A numerical investigation of the radiation characteristics of gastric, bladder and cardiac implants at 402 and 868 MHz was reported in [8]. Chirwa et al. numerically studied the radiation performance of ingested sources placed at different locations inside human gastrointestinal tract [9]. Xu et al. investigated the biological effects and the signal intensity of an ingestible wireless device when it was placed at seven positions and three orientations in the human body using finite-difference-time-domain (FDTD) method [10]. In [11], Kim and Rahmat-Samii numerically characterized the performance of a dipole antenna implanted inside human head (brain). However, the implanted or ingested medical devices in all of these papers were located in the stomach, bladder, heart, or brain, which surrounding tissue is quite different from that of the mouth [12]. Therefore results found in these studies cannot be directly applied to intra-oral devices,

and there is a need for numerical and experimental characterization of in-mouth RF transceivers.

What we present in this paper is based on the requirements of the new internal version of an assistive technology, called the Tongue Drive System (iTDS), shown in Fig. 1, which is currently under development [3]. A pair of 3-D magnetic sensors will be mounted on a flexible printed circuit board (PCB) to detect the movements of a small permanent magnet secured on the user's tongue as a tracer. The sensor outputs are digitized and wirelessly transmitted outside the mouth to a portable device, such as smartphone, by an on-board RF transmitter (Tx) to be translated to control commands [13]. The iTDS will be hermetically sealed in biocompatible materials and embedded in a dental retainer, customized to the user's dental impression. In this configuration, the RF Tx will be located between the outer surface of the user's lower teeth and the cheeks, surrounded by tooth, gum, bone, facial and tongue muscles, and skin tissue. To these we should add the flexible PCB and coating material, which can be made of a variety of polymers such as Parylene, polyimide, silicone, and acrylic. Therefore, the performance of the RF Tx is expected to be significantly affected, especially at high frequencies, and a good understanding of these effects is necessary for designing reliable wireless links for the iTDS and other wireless intra-oral devices.

We have studied the effect of human head/mouth on the radiation pattern and power of a Tx through simulations and experiments, when it was placed inside the mouth. We examined three frequencies; 433 MHz, 915 MHz, and 2.42 GHz, all of which are in the industrial-scientific-medical (ISM) because of their popularity and availability in the form of commercial-off-the-shelf system-on-chip transceivers. The next two sections describe the simulation and experimental setups, followed by the measurement results and conclusions.

II. Modeling and Simulation

A. Human Head Model

We built a simple human head model with shoulders to simulate the effects of the surrounding tissue on the Tx radiation characteristics using HFSS (High Frequency Structural Simulator, Ansoft, Pittsburgh, PA). The head model is an octagonal column with 11 cm radius and 22 cm height, separated into two parts: brain white matter (top) and muscle (bottom) to emulate human brain and mouth region respectively. Below the head, there is a $40 \times 30 \times 20 \text{ cm}^3$ rectangle filled with body fluid to mimic the upper part of the human trunk including shoulders. The geometries of the head and shoulder model is shown in Fig. 2, and Table I gives the electric properties of different human tissues used in this model at 433 MHz, 915 MHz and 2.42 GHz [12].

B. Antenna Simulation

Three inverted-F antennas (IFA), designed and optimized for 433 MHz, 915 MHz and 2.42 GHz bands, were used in our simulations as wireless sources due to lack of the HFSS models of the actual chip antennas used in measurement. Each IFA consisted of a rectangular arm connected to a ground plane ($30 \times 20 \text{ mm}^2$) on top of 1.27 mm thick Rogers RT/duroid® 6010 substrate with relative dielectric constant of 10.2 and loss tangent of 0.0023. The size of antenna board was $30 \times 30 \text{ mm}^2$, which is similar to the size of the transmitter PCB used in our measurements. To replicate the real measurement setup, in which an external battery was used to power the transmitter by a pair of wires, a 30 cm piece of wire was attached to the ground plane, hanging outside the head model for the battery connections. The antenna was encapsulated in a layer of epoxy with 2 mm thickness in all directions, which relative dielectric constant and loss tangent were set to 3.3 and 0.001, respectively. The overall dimensions of the antenna after packaging were $32 \times 32 \times 5.27$

mm³. The packaged antenna was embedded inside the head model, 3 cm above the bottom of the head and 4.8 mm from the cheek, as shown in Fig. 2.

III. Measurements Setup

A. RF Transmitter

Three small Tx modules were built and tuned to operate at 433 MHz, 915 MHz and 2.42 GHz ISM-band for in situ measurements. Both 433 and 915 MHz transmitters were based on CC1110 (Texas Instrument, Dallas, TX) which is a system-on-chip (SoC) including an 8051 microcontroller and a low power RF transceiver. The carrier frequency of CC1110 can be programmed from 391–464 and 782–928 MHz. The 2.42 GHz Tx was based on a similar SoC, CC2510, which is programmable in 2.4–2.45 GHz band. All Tx chips were programmed to operate at continuous transmission mode at the specified frequencies with 0 dBm (1 mW) output power.

To reduce the size of Tx PCBs and facilitate intra-oral measurements, we used small chip antennas dedicated to each frequency. This type of antenna is also more likely to be used in the iTDS compared to IFA for the same reason. The radiation patterns of these commercial antennas were slightly different from each other, but quite different from those of the IFAs used in our simulations. To solve this problem, instead of reporting the absolute received power values, we decided to focus on the attenuation pattern resulted from placing the Tx inside the mouth by subtracting the measured radiation patterns inside and outside the mouth. Thus, we tried to minimize the effects of the difference between the absolute radiation patterns of our simulated and measured antennas.

For short term intra-oral testing, Tx boards were coated by a ~2 mm thick layer of medical-grade epoxy (Loctite, Germany), as shown in Fig. 3. Seven AWG-30 wires were penetrating the package, five for programming the CCxx10 and the other two were the supply lines connected to an external battery. A small plastic piece was also added to each Tx module as a biting site to facilitate fixation of the Tx in the mouth. During the experiment, the subject was required to bite onto the plastic piece with his molar teeth to maintain the Tx position with respect to his head. The overall size of the packaged Tx module was 20 × 30 × 5 mm³.

B. Measurement Protocol

Measurements were carried out on a 29 years old male subject (height: 1.75 m, weight: 65 kg) in an outdoor open space on top of a parking structure to minimize environmental interference. The radiation power patterns of three different Tx modules were measured for vertical and horizontal polarization in two configurations. In the first configuration, shown in Fig. 4a, the Tx was supported by a stationary platform made of foam, which material interference can be neglected. The initial position of the Tx was tilted 45° to the left (in top-view) with respect to the receiver (Rx) in the horizontal plane, resembling its relative orientation inside the mouth. The platform was rotated clockwise manually from 0° to 360° in 15° steps, while the Rx signal strength was recorded with a monopole antenna, connected to an Agilent N1996A spectrum analyzer. The Rx antenna was mounted on a tripod and placed 1 m away from the Tx platform in the horizontal direction, and 1 m above the ground (see Fig. 4a). This is about the same height as the user's belt or wheelchair, which is where the Rx (smartphone) is expected to be located.

In the second configuration, shown in Fig. 4b, the subject was asked to hold the Tx module between his right cheek and the teeth by biting the plastic projection on the package with his molars. A pair of supply wires came out of the subject's mouth and connected to a 9 V battery, hanging ~30 cm below the head. The subject wore a neck collar to maintain his head position and avoid any unintentional head movements during measurements. Similar to the

first configuration, the subject rotated from 0° to 360° in 15° steps, with the initial position directly facing the Rx antenna (see Fig. 4b).

IV. Measurement Results and Discussion

The radiation power patterns were simulated and measured in air and in the mouth. The difference between these patterns was used to represent the attenuation caused by the human head/mouth. Figs. 5 and 6 show the azimuth radiation patterns from simulation and measurement results, respectively. The direction of the subject's nose was considered 0° . The blue (dark) and red (light) dots are the attenuations measured when the Rx antenna was placed horizontal and vertical, respectively. Lower values towards the center mean higher attenuation in that direction. Both in simulations and in measurements, the most significant attenuations (dips in the curves) occurred posterior to the head (165° – 240°) for both vertical and horizontal polarizations. This could be the result of having more tissue in the transmission path towards the back of the head than in front, where the Tx is just behind the cheek. In measurements, the maximum attenuation at 433/915/2420 MHz was $-20/-19/-26$ dB and $-24/-27/-29$ dB for vertical and horizontal polarizations, respectively. Hence, the maximum attenuation increases as the frequency increases.

Even though simulation and measurement results are more or less similar in terms of attenuation patterns, they have significant differences in magnitude. The pattern-averaged attenuation (PAA), calculated by averaging the vertical and horizontal attenuations across the entire plane, at 433/915/2420 MHz were $-26/-31/-39$ dB and $-11/-9/-12$ dB in simulations and measurements, respectively. Hence, the simulated PAAs were 15–27 dB higher than the measured values. It should also be noted that the 2.42 GHz Tx had significantly higher attenuation than its counterparts in simulations, which was expected, but not in measurements. These disagreements could be the result of oversimplification in our head model, nonlinear effects, and the errors induced in the measurements by the hanging supply wires from Tx modules, which can also behave as an antenna.

Table II summarizes the averaged anterior (270° , 0° , 90°) and posterior (90° , 180° , 270°) attenuations. The anterior to posterior ratio was in the range of -4 to -11 dB and -1 to -13 dB for simulations and measurements, respectively, and increased with frequency. We observed less attenuation in certain directions, which it is probably because of increased electrical size and efficiency of the antenna caused by the loading of human tissue [7]. This may have had a more significant impact in compensating the tissue loss in those directions since the original received signal strength in those directions was quite low.

V. Conclusion

We have numerically and experimentally investigated the effect of human tissue on the RF radiation performance of intra-oral wireless devices at different carrier frequencies. Both simulation and measurement results showed that the highest attenuation occurs in the back of the human head and increase with the frequency. 2.42 GHz Tx experiences higher attenuation than 433 MHz and 915 MHz (in simulations), while the difference between the latter is not that significant. The discrepancies between the simulation and measurement results may be caused by oversimplification of the human head and supply wires connecting the Tx to a battery. We intend to use a more realistic human head model to improve simulation results. We are also working on a new Tx module, in which a rechargeable battery is incorporated inside the package to eliminate the hanging supply wires.

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Fig. 1.
Internal Tongue Drive System (iTDS) built on a flexible printed circuit board and embedded in a dental clip.

Fig. 2.

Simplified human head model in HFSS to simulate the effect of surrounding tissue on an intra-oral RF Tx. Three Inverted-F antennas were designed to operate at 433, 915, and 2420 MHz. They were epoxy coated and embedded in the head model to be used as the source during simulation.

Fig. 3. RF transmitter module, equipped with a chip antenna and CC1110 or CC2510 microcontrollers, and then sealed by a ~2 mm layer of epoxy.

Fig. 4. Experimental setup for characterization of the intra-oral RF radiation. (a) Measurements in the air using a foam platform, (b) In situ measurements on a human subject holding the Tx module in his mouth.

Fig. 5. Simulation results of the attenuation pattern. (a) 433 MHz (b) 915 MHz (c) 2.42 GHz. Most significant attenuation was in the posterior of the head.

Fig. 6.
In situ measurement results of attenuation pattern. (a) 433 MHz (b) 915 MHz (c) 2.42 GHz.
Similar to simulation results, highest attenuation happened in the back of the subject.

Table I

Electric Properties of Human Tissue Used in the Human Model

Frequency	433 MHz		915 MHz		2.42 GHz	
Tissue	σ [S/m]	ϵ_r	σ [S/m]	ϵ_r	σ [S/m]	ϵ_r
Body Fluid	1.533	69.00	1.64	68.90	2.45	68.23
White Matter	0.454	41.67	0.60	38.82	1.20	36.20
Muscle	0.805	56.87	0.95	54.99	1.719	52.77

σ : Tissue conductivity, ϵ_r : Relative dielectric constant, Source: [12]

Table II
Simulated and Measured Radiation Attenuation in the Anterior and Posterior of Human Head

Frequency		433 MHz		915 MHz		2.4 GHz	
Polarization		V	H	V	H	V	H
Simulation (dB)	Anterior	-32.3	-14.1	-32.4	-22.9	-35.2	-32.2
	Posterior	-37.4	-18.1	-39.5	-32.6	-45.7	-43.2
	Ratio	-5.1	-4.0	-7.1	-9.7	-10.5	-11.0
Measurement (dB)	Anterior	-10.6	-8.2	-6.9	-1.84	-11.3	-3.7
	Posterior	-16.6	-9.3	-15.8	-12.3	-17.5	-16.7
	Ratio	-6	-1.1	-8.9	-10.5	-6.2	-13.0

V: Vertical polarization, H: Horizontal polarization