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In-Mouth Antenna for Tongue Controlled Wireless Devices: Characteristics and Link-Loss

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***Abstract*— We have investigated the possibility of using a curved dipole antenna inside the mouth for the tongue controlled wireless devices in 2.45GHz ISM band. These devices can be interfaced with the wheelchair or the computer used by the paraplegic patients. Two antenna placement positions have been investigated: in front of the teeth and behind the teeth. The investigations were done through the FDTD simulations on a realistic heterogeneous phantom with the mouth closed and open. The link loss between the in-mouth dipole antenna and an external dipole antenna at 400mm from the center of the head was calculated. It was found that the radiation pattern changed according to the placement of the antennas inside the mouth and whether the mouth was open or closed. The link loss for the in front of the teeth placement was found to be 9dB-11dB lower than the behind the teeth placement depending on the open or the closed mouth. The variation in the link loss was 1dB-4dB for the open mouth when compared with the closed mouth depending on the antenna placement position. By using these results, a reliable wireless link for the in-mouth device can be designed.**

I. Introduction

Spinal cord or brain injury may result in paralysis of limbs and torso affecting patients with movement disabilities. One of the possibility for rehabilitation of such patients is by using tongue controlled devices which can be interfaced with either the wheelchair or the computer [1]-[6]. These tongue controlled devices are placed inside the mouth and ought to be wireless for the ease of control and maintenance and thus the antennas in such devices plays a critical role. They typically use 2.45GHz ISM band for the communication. The in-mouth tongue controlled devices are different from the on-body or the implant devices as these are placed inside the human body but are not surgically implanted. These devices can better be described by the term semi-implantable devices. The presence of lossy tissues of the tongue, the inner-mouth and the teeth will affect the performance of the device and the antenna in a similar way to actual implanted devices.

In [7], the radiation characteristics of an intra-oral wireless device at multiple ISM bands has been presented. For the simulations, an inverted-F antenna (IFA) was used and for the measurement, a chip antenna was used. Both IFA and chip antenna are not practical solution for the in-mouth antenna due to large size (30 mm $\times$ 30 mm) of the IFA and poor performance of a chip antenna in a surrounding of lossy tissues. Also, a homogeneous phantom was used for the simulation. In this paper, we have bent the half-wave length dipole antenna to fit the periphery of the teeth. As discussed in [7], the maximum attenuation is at the back of the head, hence placing the antenna in front areas of the mouth is most appropriate to communicate with the receiver in the wheelchair or a PC. We have investigated two antenna placement positions, (a) in front of the teeth and (b) behind the teeth, with both the open and the closed mouth. The teeth here is the teeth of the upper jaw and hence the antenna will be fixed. The link loss between the in-mouth antenna for these two placement positions and an external dipole antenna at the same level of the in-mouth antenna has been estimated. All simulations were done using a realistic phantom [10] having the electrical properties of the tissues inside the mouth and the head in the commercial FDTD simulator SEMCAD [8] in 2.45 GHz ISM band.

Since the antenna will be close to the brain, specific absorption rate (SAR) has to be calculated. The radiated power should be within the limits in order to keep the surrounding tissues and the teeth healthy. We have estimated the maximum power accepted by the antenna following the SAR limitations.

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II. Numerical Phantom

For proper characterization of the in-mouth antenna, phantoms having mouth with teeth, tongue and inner air-cavity are required. For the investigation, we have used the numerical phantom named Duke provided by ITIS foundation [9] developed for the Virtual Family Project [10]. Duke is a 34 year old male heterogeneous phantom having more than 80 different types of tissues. The truncated head model of Duke is shown in Fig. 5.

III. Propagation Theory

Waves propagating from an antenna in the mouth to an external antenna will undergo losses because of the reflection, the scattering, the absorption and the pathloss. A very simple model for a mouth can be described in terms of the layered tissue which consist of the layer of the teeth, the muscle, the connecting tissues, the fat and the skin as shown in Fig. 1. There will be reflections at each of these tissue interfaces and absorption in the tissues.

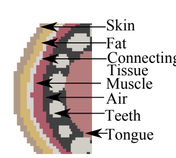

Fig. 1. Voxelled layered model showing the tissue layers

The electrical properties of these tissues is shown in Table I and has been taken from [11].

TABLE I
TISSUE PARAMETERS

Tissue	Permittivity	Conductivity (S/m)
Muscle	54.42	1.88
Connecting Tissue	26.97	0.98
Fat	5.28	0.10
Skin	38.00	1.46
Teeth	11.38	0.39

The received power by an external antenna from the in-mouth antenna at the distance d can be calculated using the Friis formula:

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi d} \right)^2 \quad (1)$$

where λ is the wavelength in the free space. The in-mouth antenna characteristics can be defined as a super-antenna consisting of the sum of the in-mouth antenna and the body [12]. In such scenarios for the far-field case, complete body can be treated as an antenna radiating to the free space. It should be noted that the Friis formula is valid for two antennas in a free space and that the transmitter gain (G_{TX}) is the gain of the super-antenna (in-mouth antenna including the body).

IV. IN-MOUTH CURVED DIPOLE ANTENNA

The standard wire dipole antenna was bent so that it follows the curvature of the teeth for easy placement inside the mouth. The in-mouth curved dipole antenna is shown in Fig. 2. The vertical length as seen in the figure of the antenna is 21.8mm which is 64% reduction of the length when compared with the free-space half-wavelength dipole at 2.45GHz. The radius of the wire was fixed at 0.3mm. The curved dipole was insulated with 0.5mm thick biocompatible insulator of permittivity 3.1. The length of the dipole was then optimized for minimal return loss in 2.45GHz ISM band by placing the antenna in front of the teeth with the mouth closed. The length was varied such that it follows the curvature of the upper jaw. The optimized antenna was then used at the other placement positions. The placement of the antenna behind the teeth and with the open mouth scenarios resulted in shifting of the resonance frequency. The return loss for the different cases is shown in Fig. 3.

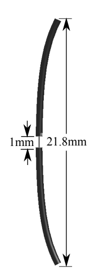

Fig. 2. In-mouth Antenna

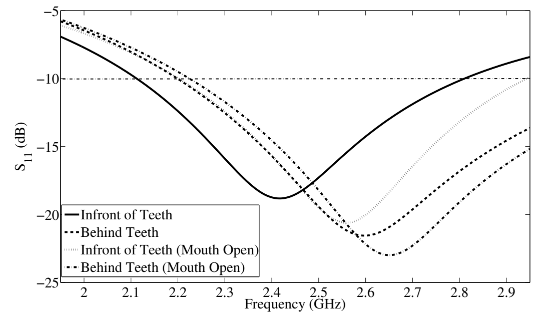

Fig. 3. Return Loss for different simulation scenarios

It can be seen from the figure that the shifting of the resonance frequency is maximum for the behind the teeth placement with the open mouth. However, the antenna still has a return loss of less than -10dB in the ISM band and can still be used for these scenarios.

V. SIMULATIONS

A. Simulation Setup

Simulations were done in commercially available numerical electromagnetic solver SEMCAD which uses the finite-difference-time-domain (FDTD) method. The antenna was modeled as a thin PEC wire. A voltage source with an internal resistance of 50Ω was used for the antenna excitation. A Gaussian sine wave with the central frequency of 2.45GHz and the bandwidth of 1GHz was used for the broadband simulation. An uni-anisotropic perfectly matched layer (UPML) was used as the simulation boundary. Only the head of Duke phantom was included in the simulation by truncating the phantom along the transverse plane by negative padding. This was done in order to save simulation time. Four different scenarios were simulated (a) antenna in front of the teeth with the mouth closed (b) antenna in front of the teeth with the mouth open (c) antenna behind the teeth with the mouth closed and (d) antenna behind the teeth with the mouth open. The placement of the antenna in front of the teeth is shown in Fig. 4. The head phantom includes the air cavities within the mouth when it is closed. Since it is not possible in the phantom to move the mandible to open the mouth, an approximate open mouth was generated by overwriting the tissues below the upper jaw by a block having electrical properties of the air as shown in Fig. 5. The block was 63mm deep into mouth with 15mm height and 50mm width.

VI. SIMULATION RESULTS

A. Gain Pattern

The gain pattern for the four different simulation scenarios for the transverse plane at the level of the antenna at 2.45GHz is shown in Fig. 6. The gain is determined in the far field of the body and thus take into account the effect of the body as discussed in the Section III. It can be seen from the figure that the gain is maximum for the antenna placement in front of the teeth with the mouth open and is minimum for the behind the teeth placement with the mouth closed. The gain for

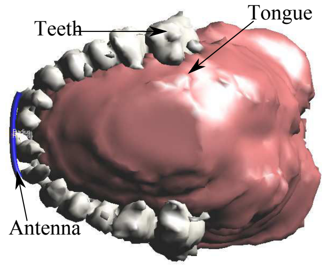

Fig. 4. The placement of the in-mouth antenna in front of the teeth

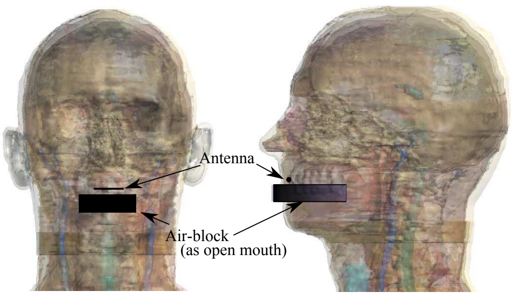

Fig. 5. Duke head with air-block as an open mouth

different scenarios at 2.45GHz at 180° (front part of the head) is shown in Table II. It should be noted that the truncated head was used for the gain calculations. Hence, the in-mouth antenna with only the head is a super-antenna. We assume here that excluding the other body parts from the simulation will not have a significant affect on the gain calculations as the currents in the torso and the lower body part will be negligible because of the high attenuation.

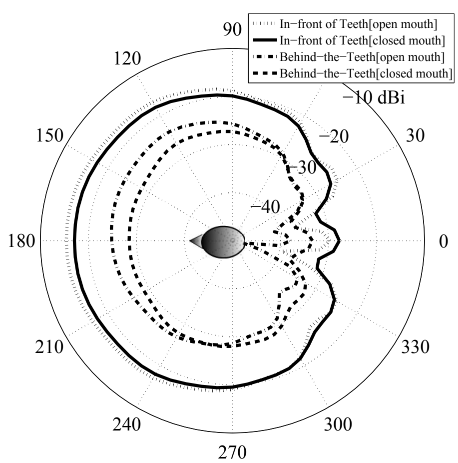

Fig. 6. The gain of the in-mouth antenna in the transverse plane at the level of the antenna

B. Link Loss

The link loss was calculated from equation 1. G_{TX} obtained from the simulation at 180° was used for the the in-mouth antenna as the receiver antenna is aligned at the same level and orientation. Thus, it is the variation of the

TABLE II
TRANSVERSE PLANE GAIN AT 2.45GHZ AT 180°

Scenario	Gain (dBi)
In front of Teeth-Closed Mouth	-17.3
In front of Teeth-Open Mouth	-15.4
Behind-the-Teeth-Closed Mouth	-28.5
Behind-the-Teeth-Open Mouth	-24.8

gain of the in-mouth antenna in different scenarios that will affect the link loss as other parameters remains constant. The receiver antenna was a half-wavelength dipole antenna with a return loss less than -10dB in the 2.45GHz band and placed at the distance of 400mm from the center of the head at the same level and the orientation as that of the in-mouth antenna. The gain of the external dipole from the simulation was found to be 1.8dB which is 0.35dB below the normal value of 2.15dB for a standard half-wavelength dipole antenna as it was calculated in the presence of the head. The distance of 400mm is a realistic distance considering the receiver which may be mounted on a computer monitor and will be approximately at the same level to that of the in-mouth device. The distance of the external dipole from the front of the outer lip was 287mm. This distance was used in the equation 1 for calculation of the link loss as this is the distance between the super-antenna and the external antenna. The simulated link loss for the different scenarios is shown in Fig. 7. The comparison between the simulated link loss and the link loss from the Friis formula using the simulated gain at 2.45GHz is shown in Table III. It can be seen that the Friis formula and the simulations agree very well and hence the link loss at any other distance can be easily estimated from the Friis formula with the simulated gain.

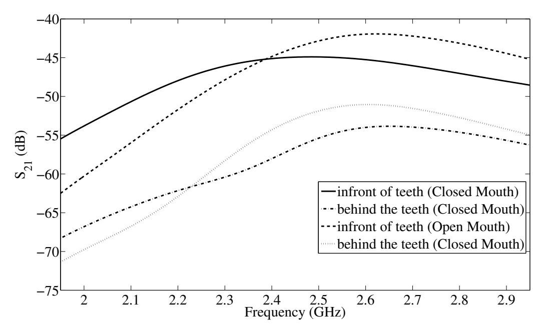

Fig. 7. Link Loss

TABLE III
THEORETICAL VS. SIMULATED LINK LOSS AT 2.45 GHZ AT 400MM FROM THE CENTER OF THE HEAD

Scenario	Friis Formula* (dB)	Simulated (dB)
In front of Teeth-Closed Mouth	-44.9	-44.9
In front of Teeth-Open Mouth	-43.0	-43.7
Behind-the-Teeth-Closed Mouth	-56.0	-56.6
Behind-the-Teeth-Open Mouth	-52.4	-52.8

*with the simulated gain

For the in front of the teeth placement, opening the mouth

TABLE IV

MAXIMUM ACCEPTED POWER

SAR Limitation	in front of teeth	behind the teeth
1.6W/Kg over 1g [closed mouth]	9.4mW	6.3mW
1.6W/Kg over 1g [open mouth]	8.3mW	5.9mW
2W/Kg over 10g [closed mouth]	40.6mW	30.6mW
2W/Kg over 10g [open mouth]	32.2mW	31.3mW

decreases the link loss by 1.2dB and for the behind the teeth placement it decreases by 3.7dB. It should be noted here that the mouth is open to a certain level only and hence opening the mouth more or less than in simulation will change the result. The variation is largely because of the gain variation in the different scenarios. The link loss for the in-mouth antenna placement in front of the teeth is lower than the behind the teeth placement for both open and closed mouth. But it can not be said that in front of the teeth placement is always a better placement position if other factors are considered. For example, for the device like [6], which is attached to the maxilla, behind the teeth placement is a good choice because placing the antenna in front of the teeth will involve extra clamps and wires going around the teeth. Behind the teeth placement is also better if cosmetics and patient's privacy is considered. Thus, there has to be trade-off between the link loss requirement and the ease with which device can be mounted inside the mouth.

VII. SPECIFIC ABSORPTION RATE

Since the in-mouth antenna is in direct contact with the body, an estimate of an appropriate power that can be accepted by the antenna without damaging the tissues is critical. The regulated spatial peak SAR limitation in Europe is 2W/Kg averaged over 10g of tissue and in USA, it is 1.6W/Kg averaged over 1g. Following these limitations we can calculate maximum accepted power by the antennas in different scenarios [13]. Table IV presents the maximum accepted power calculated in SEMCAD by fast averaging IEEE-C95.3/1528 guidelines [14]-[15]. The electrical properties of the tissues present in the head was taken from [11] and their density from the tissue specification sheet provided by ITIS foundation. The highest SAR levels were found in the teeth, the tongue and the muscle. For the antenna placed in front of the teeth, peak SAR was found in the muscle tissues of the upper lip (cf. Fig. 1) and for the antenna placed behind the teeth, it was in the tongue.

VIII. CONCLUSIONS

An antenna suitable in shape which can be fitted inside mouth with ease was presented. It was found that the antenna gain varies with the placement position inside the mouth and whether the mouth is open or closed resulting in a variation in the link loss. The link loss including these variations was found within the acceptable limit for establishing a reliable wireless communication link between the in-mouth device and an external receiver.

Future work will involve investigating the link loss to the external receiver at the different positions, for example, on the wheelchair.

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