Study of 403.5 MHz Path Loss Models for Indoor Wireless Communications with Implanted Medical Devices on the Human Body

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ABSTRACT

This paper contains simulated and measured data for 402-405 MHz radio propagation path loss in the consultation room for the allocated Medical Implant Communication System (MICS) band. The propagation models have been developed based on the number of partitions, concrete walls and objects between the transmitter and receiver. Unfurnished and furnished rooms were studied for indoor path loss and room penetration loss in a narrow band measurement. The received signals were measured, and effects from the indoor environment were evaluated to determine accurate impacts on the communication system. The fading in path loss for unfurnished and furnished indoor models with different polarizations was also considered. The path loss from the proposed models was illustrated and compared with the free space model. In this paper, the indoor wave propagation at the 403.5 MHz band was studied with both simulations and measurements to provide information that may aid the development of futuristic indoor communication for biotelemetry systems.

Keywords: Medical Implant Communication System (MICS) Band, Indoor Path Loss, Indoor Wave Propagation, Biotelemetry Systems

1. INTRODUCTION

Recently, the demands for implantable medical devices have been rapidly increasing as they play the major role in biotelemetry systems, especially when used in communication between the implanted medical devices and external systems. Wireless biotelemetry and telemedicine systems used for continuous monitoring or communicating have been widely recognized [1-9]. There is a number of medical implants currently in use and in the development stages. For example, cardiac and brain pacemakers, implantable drug pumps, artificial eyes, and cochlea implants became important functions to medical therapy and diagnosis. These medical implants continuously monitor and/or transmit a variety of physiological electrical signals from the patient's body, including heart signals (ECG or electrocardiography), brain waves (EEG or electroencephalography), and muscle response (EMG or electromyography). The implanted device transmits diagnostic information to the base station, either in one or two directions. The communication methods were mostly done by an inductive link or an RF link based on power requirements, ranges, transfer rates, and the operated frequency. The communication speed from an inductive link is up to 512 kb/s from the carrier frequency of 175 kHz, and the range of communication is in a few inches or less. The limitations of an inductive link pushed the European Telecommunications Standards Institute (ETSI) to regulate a new standard for the Medical Implant Communication System (MICS) [10-11]. The frequency band is at 402 MHz to 405 MHz with the maximum occupied bandwidth at 300 kHz (0.7% relative bandwidth). The communication range through the implanted devices is from half a meter to couple of meters, depending on losses and the surrounding environments. To accomplish the communication, path loss in the link budget needs to be investigated and calculated. It provides an idea of how the system could behave and helps us to identify the most critical parts in the system design.

The International Telecommunication Union (ITU) regulated the interference problems between MICS and the Meteorological Aids Systems (Metaids) in the document ITU-R SA.1346 [12]. It includes parameters recommended for calculating a link budget on uplink and downlink systems. The purpose is to guide the safety level for the telemedicine system in order to work properly and to minimize the risk of disturbance from harmful interfering factors. The biotelemetry operated at MICS band is different from the traditional mobile-phone channels. The system is intended solely for indoor use with both the patient and the base station in the same room, while other systems are designed for both indoor and outdoor use. The combination of the MICS band and the limited range makes the full potential use of the link budget on both possible and practical for the MICS band investigations. The system link budget consists of two main parts: the communication from transmitter to the body and from the body to the implanted module. All parameters related to the thermal noise and losses from the links, fading, and multi-path are well standardized. The ETSI document regulates com-

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munication between a base station and an implanted device with the emission power at the band edge limited to 20 dB below the maximum level of the modulated output [11]. To lower the impact of the higher noise figure, the communication speed can be reduced along with the bandwidth for an uplink from the implant. In the ITU-R document, two additional margins, an excess loss parameter and fading margin, are included to guarantee the link performance success. According to MICS standard, the Federal Communications Commission (FCC) in the USA and Australia has specified the maximum output level to 25 μW of the Equivalent Isotropic Radiated Power (EIRP) [13-14]. The EIRP level is 2.2 dB lower than the Equivalent Radiated Power (ERP) level. In addition - since the MICS and FCC defined that this 402 - 405 MHz frequency band was specified for an indoor use only - therefore path loss model is a necessary tool to be considered for designing and deploying the wireless indoor communication.

The MICS radio channel at 402 - 405 MHz has the wavelength inside the human body around 10 cm when the dielectric properties of human tissues are taken into consideration [15]. With the large attenuation from the lossy body, the distance between the patient and the base-station should be determined within a wavelength of up to 10 wavelengths when the uplink communication is activated. It extends from the absolute near zone to the far zone in some directions. Compared to the dimension of a typical consultation room, the measurement could be done from the length of a couple decimeters to the length of the whole room. It is very difficult to simulate the wave propagation within a whole room in FDTD simulations. This problem is applicable to all frequencies for the cellular phone and higher. The wavelength in the free space is around 75 cm, and therefore the dimension of a typical room can be characterized by 4 to 5 wavelengths. The path loss between the implant and the base station varies among the surrounding environments and the patient. Fading and reflections against the floor, walls, or other surfaces in the room normally introduce an additional standing wave pattern, and therefore caused the different path loss. The Friis' transmission formula was used to evaluate the free space and path loss for narrowband wireless systems [16]. The extension of Friis' transmission formula in complex form was also developed for the free space and multi-path loss model [17]. Although these models have considered the effect of multi-path fading and are thus suitable for an outdoor environment, they are not sufficient for an indoor environment, due to the reflection and absorption caused by the human body as well as a distance between items inside the room. A lossy matter from the human body not only reduces the transmission efficiency, but also highly affects multi-path waves.

Reflections against the ceiling, walls, floor, and other environments provide additional noise and gain in different wave patterns. The gain of an implanted antenna changes to different directions while assuming the highest gain in a direction toward the implanted device. Variations between patients and consultations provide different gain and path losses. The variations of the path loss constitute different types of fading when they occur over time, as is the case with patient movement [18]. Thus, patients are basically not allowed to move during the transmissions. With the transmitting antenna can be placed both in vertical and horizontal polarization regarding to the patient orientation, the receiving antenna has to move to both co-polarization and cross-polarization in order to avoid the polarization loss. The multipath waves with different angles and different positions in indoor environment were not well characterized in the literatures, especially with regard to influences from the human body. In contrast to a number of research accomplishments related to biotelemetry, studies on simulation and measurement of channel modeling used to build the communication links between implanted devices and exterior instruments for biotelemetry have not been widely reported.

This paper shows the impact of wave propagation on the human body in an indoor environment with the receiving antenna placed on the human body and the transmitting antenna mounted on the base station. In order to know the impact it has on the channel, the variations of the path loss constitute different types of fading when they occur over time [19], as is the case with patient movement. These variations are investigated in this paper. This paper is organized as follows. In section II, the FDTD simulation is done in an empty room and in a furnished room. Next, the measurement comparisons between these two types are shown in section III. Finally, the conclusion is given in section IV.

2. SIMULATIONS IN THE MICS BAND

The Finite Different Time Domain (FDTD) simulation was made in order to characterize the radio channel for the MICS band. The frequency of 403.5 MHz or the mid-band of 402 to 405 MHz was used since the band is quite narrow. A typical consultation room at a hospital has the dimensions of 250 cm by 350 cm by 300 cm. A consultation room model is shown in Fig. 1. The grid model was divided into a small uniform cell with a size of 2 cm $\times$ 2 cm $\times$ 2 cm. The longer wall (350 cm in dimension) has a door and window on the side of the corridor. The floor, walls, and the ceiling are made of concrete. In Fig. 1, two walls and the ceiling are removed for clarity. The wave propagation and its channel were simulated both with and without furniture. The unfurnished consultation room has only a leather chair with four metal legs for the patient and dipole radiator on the base station. A leather bed, a wooden table, and a leather chair with four metal legs were added into the furnished room. Six different materials were used in the simulations as dielectrics: wood, concrete, leather, glass, gypsum and metal. The dielectric properties are given in Table 1.

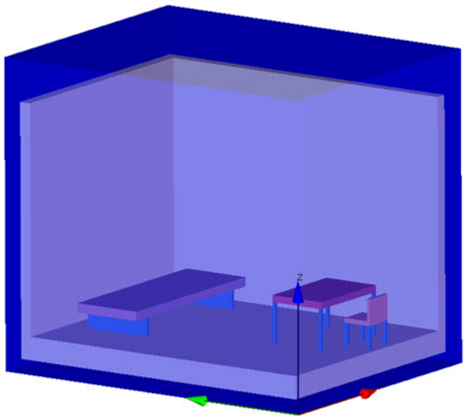

Fig.1: *CAD model of the furnished consultation room.*

Table 1: *The dielectric parameters of the consultation room used in the simulations.*

Object	Material	Permittivity	Conductivity
Bed	Leather	46.5	9.6
Ceiling	Concrete	6.0	1×10^{-2}
Chair	Leather	46.5	9.6
Door	Wood	23	1×10^{-11}
Floor	Gypsum	4.0	1×10^{-2}
Leg	Metal	1.0	9.8×10^{5}
Table	Wood	23	1×10^{-11}
Wall	Gypsum	4.0	1×10^{-2}
Window	Glass	5.5	1×10^{-1}

The link channel was simulated with the half-wavelength dipole antenna on plastic stands and the implanted PIFA antenna inside a cube of 2/3-muscle represented as the patient's body. The 2/3-muscle model is a simplified planar geometry for skin, fat, and muscle tissues and has a dimension of 12 cm × 10 cm × 5 cm. It provides useful capabilities to perform parametric studies and lower the simulation time. The electrical characteristics of the human tissue-simulating fluid, which was made from sugar, salt, deionized water and TX-151 powder, are 46.4 for permittivity and 0.464 S/m for conductivity at 403.5 MHz [20]. The antenna configuration is shown in Fig. 2. The device is implanted close to the skin between fat and muscle tissue. The location is on the chest, slightly below the collarbone. The direct path or line of sight from the implanted antenna to the dipole was used to investigate the channel behavior. The metal material was modeled as a perfect electric conductor or PEC. The FDTD simulations provide the result in terms of E-field and thus the equivalent received power is calculated as (1).

$$P_{rec} = \left(\frac{E^2}{Z_{air}} \cdot k \cdot \lambda^2 \right) \quad (1)$$

Where k is the dipole factor: 0.13 [21], Z_{air} is the intrinsic impedance of the air: 377 Ω, and is the wavelength in air: 0.74 m. The path loss is calculated from the received power by subtracting the gain from Tx and Rx antennas. The maximum gain of the implanted antenna was calculated by a transient FDTD simulation at the frequency of 403.5 MHz, the center of the MICS band. The ideal dipole has a gain of 2.15 dBi and the implant microstrip antenna has a gain of 1.67 dBi [15]. The transmitted power from the implant is set to -3 dBm or 500 μW. The transmitted power usually depends on the performance of the antenna and the circuit, the available power from the battery, and the distance to the station. There is no regulation from the MICS standard based on the transmitted power level, except that the EIPR level should have a margin of 16 dB or more in order to conserve the battery in the implanted device and to protect the surrounding tissue. The gain is calculated with the assumption of optimal polarization matching between the receiver and the transmitter. The base station is attached with an idea dipole with the patient laying down on a bed or sitting on a chair at the same height as the base station. In order to evaluate if the room's environments interfered with the antenna patterns and the channel, the simulations were done both with and without furniture. The simulated value along the direct path is shown in Fig. 3.

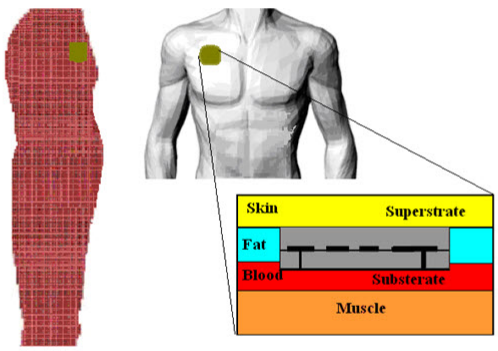

Fig.2: *Antenna configuration*

The effects of multi-path from different angles and different positions were ignored. The result in Fig. 3 shows that the placements of the dips are similar, and overall levels of field are slightly higher in the unfurnished case. These are attributed to reflection and absorption in the furniture. The values of conductivity used in the simulation affect the phase of the reflection of the wave against the wall and contribute to the standing wave pattern. In addition there is no coupling in the simulation and it was assumes that the E-field is constant along the antenna. Therefore, it is necessary to simulate a channel within the MICS allocation where the same room and antenna configuration were not changed to lower the effects of the standing wave.

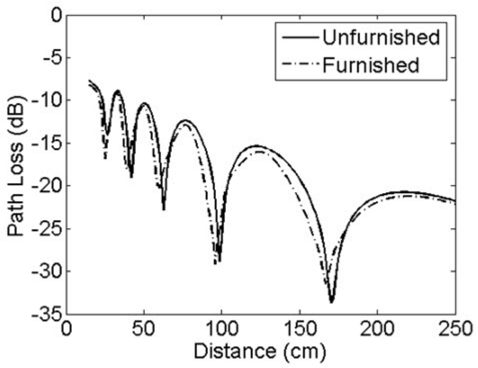

Fig.3: *The received power from the direct path in the unfurnished and furnished rooms*

3. MEASUREMENT RESULTS

In order to evaluate if the room environments interfered with the patterns and polarization, the measurements were done both with and without furniture. The stationary was set in both vertical and horizontal polarization for the transmitting antenna, while the receiving antenna was moved to align with co-polarization and cross-polarization. It was set as the patient either standing in front of the base station or laying on a bed at the same height. In this work, the height of both antennas from the floor is 150 cm. Similar to the simulation set up, the channel was measured with a dipole and PIFA antennas at the center frequency of 403.5 MHz. The PIFA antenna was fed with a -3 dBm continuous wave signal from HP 8640B signal generator. The movable dipole antenna was connected to the receiver in the zero span mode. Measurements were done with the received signal only, and the time delay was not included in the link due to the symbol time. The delayed signal does not have enough power to interfere the channel since it has to be reflected many times.

The near field measurements in an empty room were evaluated first to verify the backscattering effect. Two configurations were characterized to minimize the stochastic measurement noise and other interferences. First, the spectrum analyzer sampled an average value of the measurement results, and second the antenna was moved and measured every 30 mm. The total of 75 measurement points is consistent for the channel along the path. The comparisons of simulated and measured path loss along path in an empty room and furnished room are plotted in Fig. 4 and Fig. 5, respectively. The free space loss with an additional excess loss was calculated and added into the Fig. 4 to provide the difference between the theoretical ideal and the measurements. The theoretical loss model has no reflections from ceiling, wall, window, door, and floor.

The results in Fig. 4 and Fig. 5 showed that the values agree well and the varying patterns are close to their dips. The differences are not in a significant degree and thus acceptable. The differences are probably from the noise floor of the spectrum analyzer, effect of interferences, and effects from the reactive near-field that influenced the loss values. The path measurements with vertical and horizontal transmitting polarization were done in an empty room. Measurements were taken for both the co-polarization and cross-polarization. The results are shown in Fig. 6 and Fig. 7. In the furnished room, only the vertical polarization was measured and plotted in Fig. 8. Similar to the simulations, the resulting measurements indicated the same shape of the spatial patterns, but the furnished room provided more attenuation and altered the standing wave pattern, thus lowering the field levels. The furniture with metal frames or metal structures can partially absorb transmitting field and can consequently be the cause of difference in path loss. The differences between the vertical and horizontal co-polarization were observed. The dip and curve differ a lot further down along the path from the PIFA antenna. It shows that the pattern is not symmetric and similar to a plane through the consultation room at the height of the dipole antenna which is affected by the antenna pattern. This is due to the polarization of the dipole antenna, which is horizontally polarized. It is obvious that the wave propagation at the MICS band in a small room corresponding to the wave length and the path loss is complicated. Based on the measured results, to achieve the lower path loss and better communication between biotelemetry devices and telemedicine systems, performing co-polarization is deemed necessary.

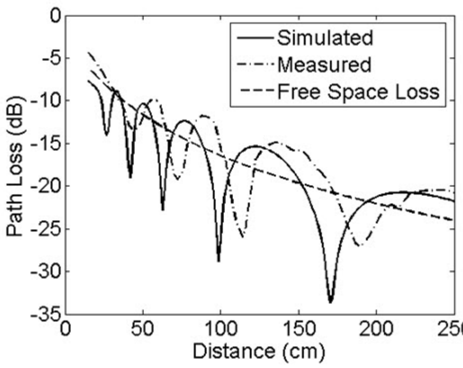

Fig.4: *Comparison of simulated and measured path loss in an unfurnished room and theoretical free space loss model.*

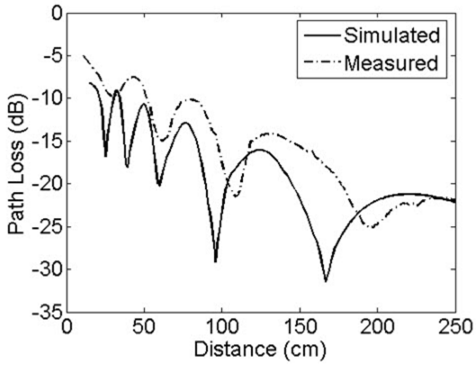

Fig.5: *Comparison of simulated and measured path loss in furnished room.*

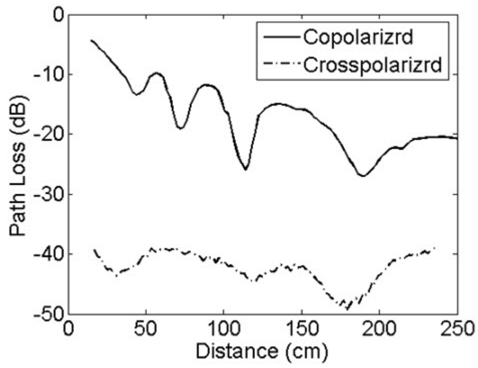

Fig.6: *Measurement with vertical transmitter polarization in an unfurnished room.*

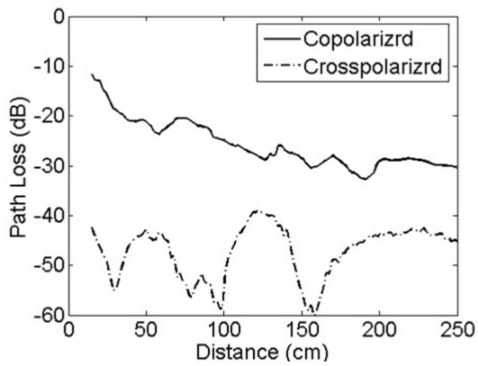

Fig.7: *Measurements with horizontal transmitter polarization in an unfurnished room.*

4. CONCLUSION

This paper has presented the simulation and measurement results of the standing wave pattern in both empty and furnished consultation rooms. Detailed measurements were made and compared in the 403.5 MHz MICS band. A difference of the standing wave pattern corresponding to the path loss between two polarizations was investigated and quantified for indoor path loss in consultation rooms. This work also determined how path loss from the proposed model

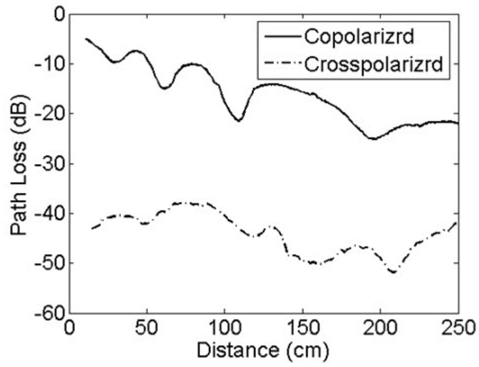

Fig.8: *Measurements with vertical transmitter polarization in furnished room.*

compared to the theoretical free space model. The dipole antenna was selected as a transmitted radiator on the base station and the PIFA antenna was used as a receiver. Results show that, at 403.5 MHz, the furnished consultation room attenuates signal between 14 and 22 dB, depending on the material and the height of the receiving antenna. The polarization results indicate that the patient and base station should at least cooperate in terms of polarization diversity to accommodate for the polarization loss. The plane variation coincides with the patient laying down or standing in front of the base station.

The evaluation of path loss shows attenuation factors and allows us to predict path loss in terms of free space path loss and excess loss. These losses represent antenna misalignment, obstructions from the path of the propagation environment, polarization losses from the medical implant. Propagation models developed in this paper may aid in the site planning of indoor wireless MISC systems. More path measurements in similar and different consultation rooms are required to determine the effects of multi-path propagation for accurate propagation prediction. The added margins to the link budget such as the effects from body movement and body size were not included. These variations may not affect a specific communication but are recommended to include in link budget calculations for future work.

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