Electromagnetic Wave Propagation of Wireless Capsule Antennas in the Human Body

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***Abstract*- Wireless Capsule Endoscopy (WCE) uses an ingestible small capsule-shaped device to detect various diseases within the digestive system. It is superior to traditional endoscopy as WCE lacks the limitations of traditional wired diagnostic tools, such as the cable discomfort and the inability to examine highly convoluted sections of the small intestine. However, a number of obstacles still need to be overcome to improve the clinical applications. This paper attempts to investigate the performance of a WCE system by studying its electromagnetic (EM) wave propagation through the human body, which allows the capsule’s positioning information to be obtained. The WCE transmission channel model is constructed to evaluate signal attenuations and to determine the capsule position.**

I. INTRODUCTION

The use of endoscopes to examine the body’s internal organs dates back to the 19th century [1], where a Mainz scientist developed the ‘Lichtleiter’ to examine human bladder and bowel with candle light. Later, various types of endoscopes were developed to examine the body’s internal organs in greater detail. Timely detection and diagnosis are extremely important since the majority of gastrointestinal (GI) cancers are curable if caught early. Surgical treatments through the use of endoscopies were developed into two branches: gastroscopy for examining the stomach and colonoscopy for the colon. Each branch developed rapidly in the last two decades, eventually culminating in the birth of capsule endoscopy. Compared to earlier techniques, capsule endoscopy is non-invasive and hence more comfortable to patients. It can examine deeper GI tracts in the human body inaccessible with existing wired endoscopes.

Wireless Capsule Endoscopy (WCE) is a technique in which a small capsule-shaped device containing a video camera, LED lights, a power source and a wireless transmitter, is ingested in order to detect various diseases within the digestive system (e.g. in duodenum, jejunum, ileum, etc.). There are many different types of WCE systems and they are mostly developed and manufactured by Olympus, Intromedic and Given Imaging. Although this technique develops very fast, there are still some drawbacks limiting the application of WCE. First of all, the collected physiological data, such as the GI tract images, are insufficient for clinical diagnosis without the presence of capsule positioning data. Secondly, most capsules are powered by an internal battery that restricts the capsule miniaturization. Lastly, current systems do not have continuous communication due to random orientations of the capsule [2].

This paper investigates the performance of a WCE communication system by studying its EM wave propagation. This investigation serves to determine signal attenuation and capsule position. There are two main reasons for this proposed research. The first one is that some EM energy is absorbed by the organs when waves are transmitted through the human body, which could lead to large signal distortions. In addition, the human body is a frequency dispersive system with frequency dependent dielectric properties (i.e. permittivity and conductivity) [3] that influence the electrical and magnetic properties of the signal transmission channel. The parameters change when wide-band signals are applied to the system, which require human body models to simulate the signal transmission with frequency dependent permittivity and conductivity. Furthermore, positioning of the capsule in the human body can be achieved by studying the EM wave propagation of the system, enabling tracking of position and orientation of the capsule without adding additional sensors. This allows more capsule space to be allocated for other components.

For the above reasons, this project works through three aspects. Firstly, the level of signal attenuation in the transmission system is investigated. Secondly, the EM wave propagation properties of WCE with different transmission distances when the transmitting and receiving antennas are in the same work plane ($z=0$ plane) are evaluated through simulation. Lastly, the second step is repeated but with varying work planes to simulate cases where the transmitting and receiving antennas are not in the same plane ($z\neq0$ planes).

II. WCE COMMUNICATION SYSTEM MODEL

EM wave propagation of the WCE transmission channel is studied by examining signal distortions, extracting the WCE’s location information and determining the capsule position. Therefore, a WCE communication system is built with a transmitter, a receiver and a communication channel in the following subsections.

A. EM wave propagation environment

The abdominal environment is highly complex and the small intestines, which lie in close proximity, greatly influence the performance of the capsule. Therefore, the inhomogeneous human body module is simplified to a homogeneous body model which uses muscle material whose relative permittivity equals 56 and conductivity equals 0.83 S/m [4]. Based on previous studies, the shape of the body model, cylinder or elliptical cylinder, does not influence the results much. In this paper, a cylinder with the radius of 100 mm is used as the human trunk model.

B. Transmitting and Receiving Antennas

To implement the communication system, suitable transmitting (TX) and receiving (RX) antennas are selected to operate in the human body environment. The WCE antenna should be less sensitive to human tissue influences as the EM wave transmits in the body. Lossy dielectric material absorbs a number of waves and thus attenuates the receiving signal, causing strong negative effects on the EM wave propagation. A much wider bandwidth is required to enable transmission of high resolution images and large amounts of data. The detection of transmitted signal is preferred to be independent of the transmitter's position and hence, the transmitting antenna should have an omnidirectional radiation pattern.

Two sets of transmitting and receiving antennas are selected for the study of the communication system: a pair of spiral antennas designed by Yoon [4] and a pair of planar antennas proposed by our group [5].

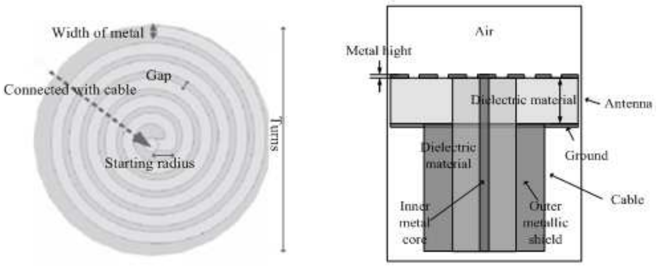


Figure 1. Top and side views of the spiral antenna [4]

The top and side views of the spiral antenna are illustrated in Figure 1. By adjusting the parameters, the antenna can be tuned to work at 403 MHz with 85 MHz bandwidth. In section III, the spiral antennas are used as TX and RX to investigate the signal transmission in the WCE system.

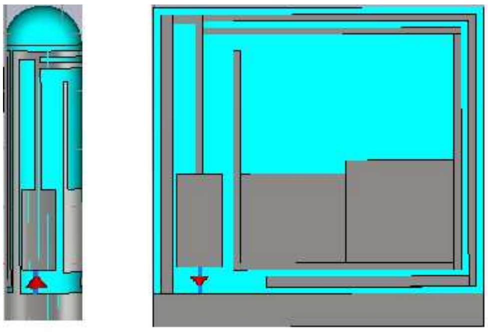


Figure 2. Rolled and planar microstrip line antenna [5]

A carefully designed planar microstrip antenna (as shown in Figure 2) can also be used in the WCE system. It is rolled up and attached to the surface of the capsule shell to work as the transmitter, as shown in the left of Figure 2. When working as receiver, the planar structure (in the right of Figure 2) is used. The center operating frequencies of these two antennas are 410 MHz and the bandwidths are more than 180MHz. It is used in section III.C to compare with spiral antennas.

C. The two-port network for WCE communication system

The communication system including the transmitter (TX), the intermediate material and the receiver (RX) can be considered as a two port network as shown in Figure 3.

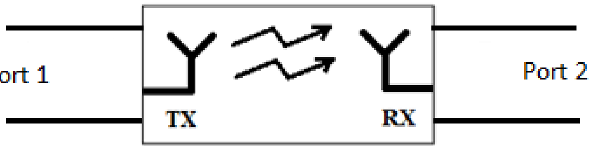


Figure 3. The two-port network of the WCE system

The terminal of the TX's cable is set as the port 1, whilst port 2 is at the end of RX's cable. Therefore, S-parameters can be used to analyze this system. S11 is the return loss used to determine the channel bandwidth. S21 the forward transmission parameter is used to evaluate the signal transmission between TX and RX.

III. EM WAVE PROPAGATION EVALUATIONS

A. Relative angle position between TX and RX (z=0 plane)

Antennas are not symmetrical in general; therefore the influence of the antenna radiation pattern (RP) should also be taken into consideration. To test the system, one direction of the transmitter with the appropriate radiation pattern is chosen. Excitation signals are supplied into the transmitting antenna while signals at the receiving antenna are compared to the input signal to check for attenuations. The receiver is placed in z=0 plane at different angles, surrounding the transmitter and separated by 45 degrees each (illustrated in Figure 4).

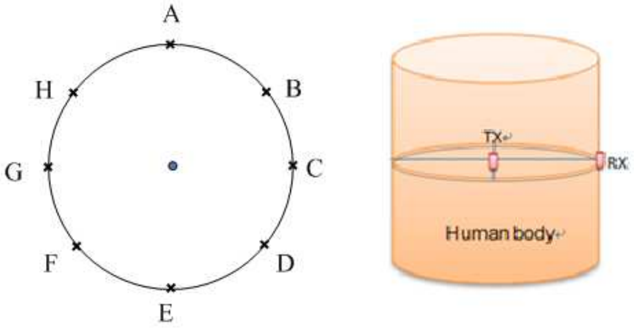


Figure 4. Testing points for evaluating the RP effects

The calculated forward transmission parameters S21 at 403 MHz are plotted in below of Figure 5, and compared with the transmitter's directivity calculated at different angles in the examined plane (as plotted in above of Figure 5).

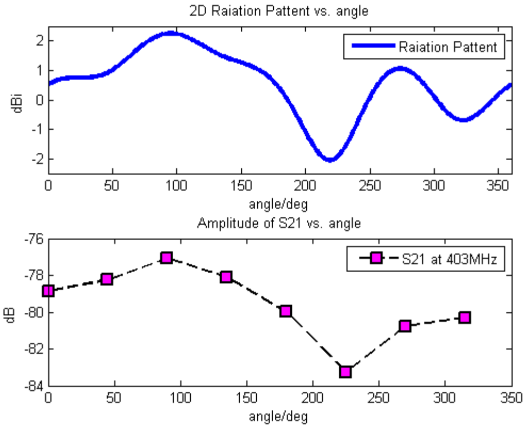


Figure 5. Radiation pattern's 2D plot vs. S21 at 403MHz

According to the results shown in Figure 5, the S21 is almost proportional to the radiation pattern of tested antenna plane when the receiving antenna is placed at different positions. The unstable forward voltage gain influences the accuracy of localization results. If the capsule is rotated around the center of the outer shell, errors are introduced to the localization calculations. This influence needs to be taken into consideration while performing the localization estimation.

B. *Relative Distance between TX and RX (z=0 plane)*

At this stage, different offsets between transmitter and receiver are applied to this system to collect the simulation results of S21. To perform capsule localization, signal transmission distances are swept from 0 to 160 mm with 20 mm steps. With the position of RX fixed, TX is moved in the human body model to obtain the EM wave propagation properties of WCE with different offsets as shown in Figure 6.

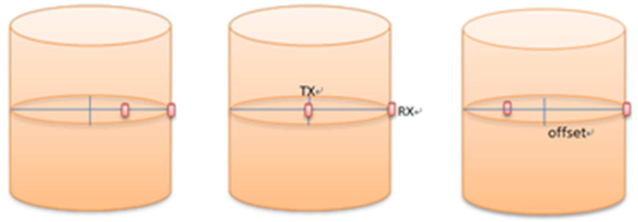
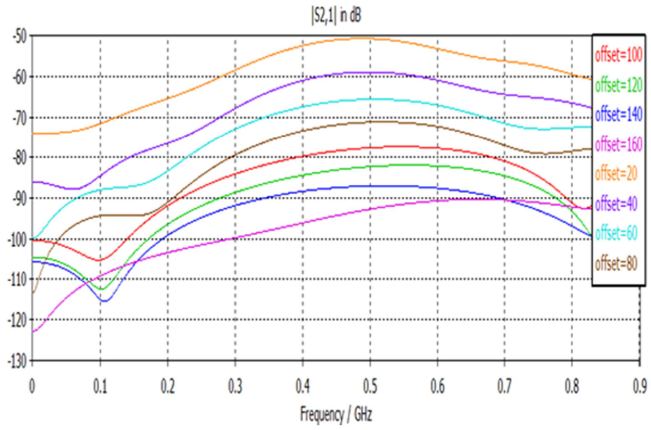


Figure 6. Layouts of TX and RX (offsets: 50, 100, and 150 mm)



The simulation results of S21 at different frequencies are shown in Figure 7.

Figure 7. S21 (in dB) vs. various offsets between TX and RX

It can be observed that within 300 MHz to 500 MHz, the S21 results are regular and do not have sudden changes. Hence, these groups of data are used to fit the channel transfer function and used in the evaluation of the communication system. Curve fitting is performed based on the Least Mean Square criterion, and the fitted transfer function is a function of frequency (*f*) and offset (*r*) as follows:

$$S21(f,r)(\mathrm{dB}) = 20\log_{10}(c_1(f)r^{-2} + c_0(f)) \qquad (1)$$

where, *r* is offset in mm, and *f* is frequency in Hz. $c_1(f)$ and $c_0(f)$ are the frequency dependent coefficients:

$$c_1(f) = -18.72f^2 + 20.31f - 3.699$$

$$c_2(f) = 0.0008371f^2 - 0.0008211f + 0.0001555$$

S21 calculated from the transfer function and S21 obtained from simulation are compared in Figure 8.

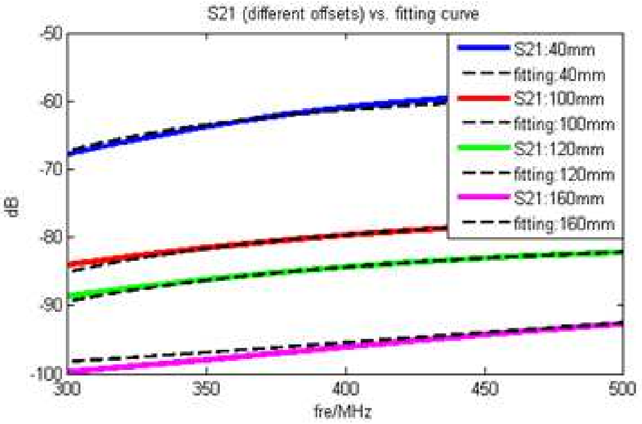


Figure 8. Fitted transfer function compare with simulated S21 (offset: 40, 100, 120 and 160mm)

Figure 8 reveals the compared S21 results calculated from the transfer function and the results achieved by simulation using Gaussian signal as the excitation signals. Based on the transfer function, the position of TX can be estimated according to the received signal.

C. *Relative Position between TX and RX (z≠0 plane)*

Since the position of the capsule endoscope in the gastrointestinal tract is changing, knowing the transmission characteristics of the wireless signal in the same plane is not sufficient. The step in Section III.B will be repeated but with the TX and RX in different planes so that the location and quantity of the receiver and transmitter can be determined.

Three-dimensional positioning and tracking of the capsule endoscope is therefore possible.

Moving TX with RX fixed is equivalent to moving RX with TX. In this study, for the simplicity of modeling, the TX is fixed at the center of the body model. As RX moves along the z-axis, the radio propagation properties of WCE with different signal transmission distances when the transmitting and receiving antennas in the different plane (z≠0 plane) can be obtained. The forward transmission coefficient S21 at specific frequency can be obtained from the simulation, which is related to the radiation patterns of TX, RX and the distance between them.

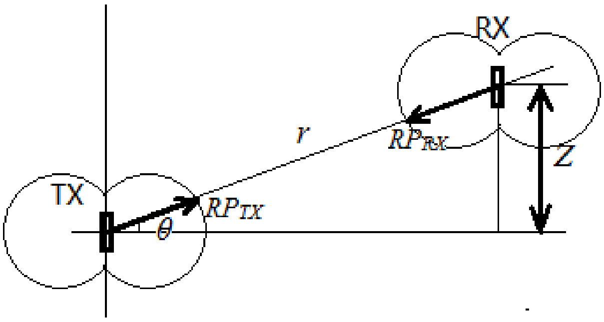


Figure 9. The relationship between RP_{TX} and RP_{RX}

As illustrated in Figure 9, RP_{TX} is the directivity of TX at angle θ, and RP_{RX} is the directivity of RX at angle $\pi+\theta$, S_{RP} is the sum of them. S_{RP} and S21 are plotted and compared in Figure 10.

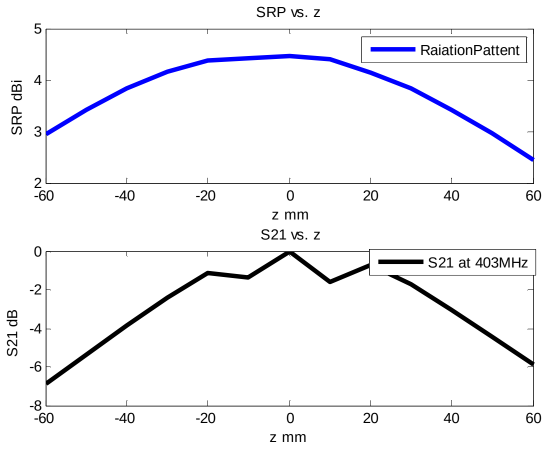


Figure 10. S_{RP} and S21 VS z for spiral antenna pair

Both SRP and S21 have peak value at z = 0 mm, and reducing with the increasing z. Irregular values of S21 are observed at z = ±10 mm, which is probably due to the ground plane shielding effect of the spiral antenna. By replacing the spiral antenna with the microstrip antennas, the irregular drops at z = ±10 mm disappear as shown in Figure 11.

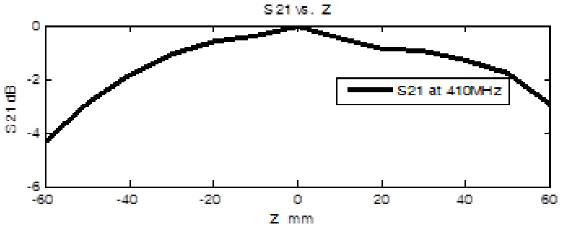


Figure 11. S21 VS z for microstrip antenna pair

On the basis of the Friis formula, the total loss between the transmitter and receiver is related to the distance between TX and RX, and the radiation patterns of them. It is assumed that there must be a linear relationship between the S21 (in linear) and S_{RP} (in linear). Using curve fitting based on the Least Mean Square criterion, the relationship is obtained:

$$S_{21(linear)} = 0.0001 S_{RP(linear)} - \frac{0.0056}{r}$$

IV. CONCLUSIONS

This paper investigated the performance of a WCE system. Based on this investigation, the capsule's positioning information can be obtained. The WCE transmission channel model was constructed in order to examine signal attenuations and determine capsule position. The outcome of this investigation will be useful for researchers to carry out further research in locating the WCE position within the human body.

ACKNOWLEDGMENT

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