NEAR FIELD RADIO LINK PROPAGATION MODEL FOR WIRELESS CAPSULE ENDOSCOPY

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

DECEMBER 2021

DEDICATION

This thesis is dedicated to both of my parents that working very hard every day in order to raise me into who I am now.

ACKNOWLEDGEMENT

I am indebted and grateful to many people, who have helped me during the course of this research project in one way or another. In particular I would like to acknowledge and express my deepest gratitude to my supervisors, Ir. Dr. Kamilia binti Kamardin and Professor Dr. Yoshihide Yamada to whom I am greatly indebted for giving me the opportunity to undertake the research in UTM under their supervision and for their encouragement throughout the course of the research.

I also would like to express my deep and sincere thanks to the grants from Ministry of Higher Education Malaysia through Fundamental Research Scheme (FRGS/1/2018/TK04/UTM/02/16) (R.K130000.7843.5F063) and Universiti Teknologi Malaysia (Q.K130000.2643.16J46). The funding received from them helped me a lot in obtaining the materials needed for my research.

Last but not least I would like to thank my parents, Kamaruddin bin Said and Zawati binti Karim, my brother and my sister for their patience, understanding, love and constant encouragement. Finally, I would like to thank everyone that has been involved in this project directly or indirectly for their help and contribution. Thank you very much.

ABSTRACT

Wireless Capsule Endoscopy (WCE) is used widely as an implantable medical device to diagnose any irregularity inside the gastrointestinal tract in the human body. The distance between transmitter and receiver antenna, operating at 402 MHz, is considered to be in the near field region due to the distance being shorter than the wavelength. The previous radio link estimation by using the Friis equation is debatable in the near field situation. The radio link calculation method in the near field region is investigated in this research. Normal Mode Helical Antenna (NMHA) is proposed as the antenna used for the application in WCE due to its ability to be designed in small size and high efficiency. The designed transmitter NMHA is placed within a human body phantom with a dielectric constant (ε_r) of 11.6 F/m that represents fat tissues. The receiver NMHA is placed outside the phantom at a distance of 0.1 to 1.0 m from the transmitter. To establish a link budget for this condition, important parameters such as received power (P_R), transmitted power (P_T), the efficiency of the transmitter antenna (η_T) and receiver antenna (η_R), reflection loss at the boundary which includes transmitted signal from vacuum to phantom (T_1) and transmitted signal from phantom to free space (T_2), dielectric loss (L_σ), spherical spreading of power, power density (W), and effective antenna aperture (A_e) are investigated. Based on the electromagnetic simulation results, the distance dependency of W is examined and the result of $W \propto 1/(distance)^2$ is obtained. As for the simulation results for A_e, the relation of A_e of the receiver antenna is examined at different distance points and results of A_e = -30 dB is obtained. The simple equation of A_e is derived. The radio link equation is formed by employing W, A_e and other propagation loss factors of a medium that is presented in this thesis. The proposed equation is then compared with the power received, P_R and S_{21} obtained from simulation. The calculated and simulated S_{21} obtained at distance 0.1 m for fat phantom is -53.6 and -53.3 dB respectively. To validate the link design equation, different human body cases such as skin and stomach are studied. The calculated and simulated S_{21} results for skin phantom are -57.3 and -56.6 dB while for stomach phantom are -50.1 and -50.2 dB. The agreement between the calculated and simulated results shows that this equation can be used in the near field region. The proposed equation also agrees well for all three tissues.

ABSTRAK

Wireless Capsule Endoscopy (WCE) digunakan secara meluas sebagai peralatan perubatan yang dapat digunakan di dalam tubuh manusia untuk mendiagnosis sebarang masalah yang mungkin wujud di dalam saluran gastrointestinal. Antena pemancar dan penerima beroperasi pada 402 MHz. Jarak di antara antenna pemancar dan penerima dianggap berada di kawasan medan hampir kerana jarak radius kurang dari saiz gelombang. Persamaan yang sedia ada untuk anggaran pautan radio menggunakan formula Friis di kawasan medan hampir boleh dipersoalkan. Justeru, kajian ini menyelidik kaedah pengiraan persamaan radio di kawasan medan hampir. Normal Mode Helical Antenna (NMHA) dicadangkan sebagai antena yang digunakan untuk aplikasi dalam WCE kerana kemampuannya untuk dibina dalam ukuran kecil tetapi mempunyai kecekapan yang tinggi. Pemancar NMHA diletakkan di dalam model badan manusia dengan pemalar dielektrik, ε_r 11.6 F/m yang mewakili lapisan lemak. Penerima NMHA diletakkan di luar model badan manusia pada jarak 0.1 hingga 1.0 m dari pemancar. Untuk menentukan anggaran pautan untuk keadaan ini, parameter penting seperti kuasa terima (P_R), kuasa dihantar (P_T), kecekapan antena pemancar (η_T) dan antena penerima (η_R), kehilangan pantulan di sempadan yang merangkumi isyarat dihantar dari vakum ke model (T_1) dan isyarat dihantar dari model ke udara (T_2), kehilangan dielektrik (L_σ), penyebaran kuasa sfera, ketumpatan kuasa (W) dan apertur antena (A_e) disiasat. Berdasarkan hasil simulasi elektromagnetik, kebergantungan jarak W diperiksa dan hasil $W \propto 1/(jarak)^2$ diperoleh. Bagi hasil simulasi untuk A_e, hubungan A_e diperiksa pada titik jarak yang berbeza dan keputusan A_e bersamaan dengan -30 dB diperolehi. Persamaan yang diselidik kemudian dibandingkan dengan kuasa yang diterima, P_R dan S_{21} yang diperoleh dari simulasi. S_{21} untuk tisu lemak bagi pengiraan dan simulasi pada jarak 0.1 m diperoleh sebanyak -53.6 dan -53.3 dB. Bagi mengesahkan ketepatan persamaan, model tubuh manusia yang berbeza seperti kulit dan perut dikaji. Keputusan S_{21} yang dikira dan disimulasikan ialah -57.3 dan -56.6 dB untuk kulit manakala untuk perut ialah -50.1 dan -50.2 dB. Kesepakatan di antara hasil yang dikira dan hasil yang disimulasikan menunjukkan bahawa formula ini dapat digunakan di kawasan medan hampir. Persamaan yang dicadangkan juga sepakat dengan ketiga-tiga tisu.

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LIST OF ABBREVIATIONS

MICS	-	Medical Implant Communication Service
MoM	-	Method of Moment
NMHA	-	Normal Mode Helical Antenna
RF	-	Radio frequency
RX	-	Receiver antenna
TX	-	Transmitter antenna
UWB	-	Ultra-wideband
VNA	-	Vector Network Analyser
WCE	-	Wireless Capsule Endoscopy

LIST OF SYMBOLS

μ	-	Permeability of a material
A_e	-	Effective antenna aperture
A_P	-	Surface dimension of receiver antenna
C/N_0	-	Carrier to noise ratio
D_0	-	Directivity
f	-	Frequency
G_R	-	Receiver's gain
G_T	-	Transmitter's gain
L_S	-	Spherical spread of power
L_σ	-	Dielectric loss
L_f	-	Free space path loss
n	-	Path loss exponent
N_0	-	Noise power density
PL	-	Path loss
P_R	-	Power received
P_T	-	Power transmitted
d	-	Distance from the transmitter antenna
R_a	-	Radiation resistance
R_D	-	Radiation resistance of the small dipole
R_{in}	-	Input impedance
R_l	-	Ohmic loss of a wire
R_L	-	Radiation resistance of the small loops
S_{21}	-	Forward transmission coefficient
T	-	Transmission coefficient
T_1	-	Transmitted signal from capsule to phantom
T_2	-	Transmitted signal from phantom to free space
W	-	Power density
X	-	Zero-mean Gaussian variable
X_C	-	Capacitive reactance
X_L	-	Inductive reactance

z	-	Thickness of the material
α	-	Attenuation constant
R	-	Reflection coefficient
ε_r	-	Permittivity
η_R	-	Efficiency of the receiver antenna
η_T	-	Efficiency of the transmitter antenna
λ, λ_0	-	Wavelength in free space
λ_g	-	Wavelength in human body
σ	-	Conductivity
ω	-	Angular frequency

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Implantable medical device is a device that is installed medically or surgically in the body and intended to remain in there for a certain time after the procedure (1). Wireless Capsule Endoscopy (WCE) is one of the medical devices that has the purpose of diagnosing the health conditions inside the gastrointestinal tract (2–4). Although WCE is already in the market as of today, the development to improve the capability of WCE still goes on (5).

Medical devices such as WCE that need wireless imaging and monitoring, capability for the antenna to work at close distance is demanded (6). Figure 1.1 shows the illustration of WCE system configuration where the capsule is swallowed by a patient and data captured by the capsule is transmitted to the receiver outside the body. Evaluation of link budgets in the near field by (7) and (8) based on Friis equation and numerical evaluation using simulation software, FEKO. The evaluation shows that the Friis equation is possible to use in the near field with some adjustments on the original equation but the research is based on the antenna in free space, not in the human body. Thus, link budget equation for near field and in the human body is desirable.

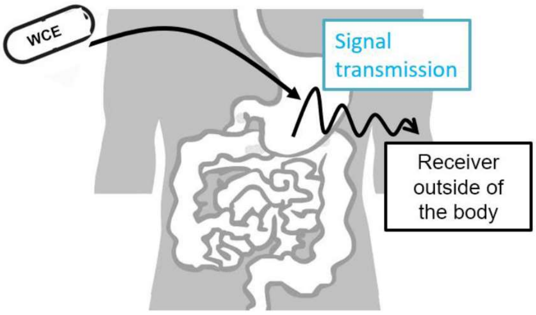

Figure 1.1 WCE system configuration

Figure 1.2 shows one type of WCE on market and its internal architecture (9). From the cross-section image, it can be seen that the antenna is one of the important components for WCE. Characteristics of an antenna that can be used for WCE application needs to be miniature in size with high bandwidth and efficiency (10,11).

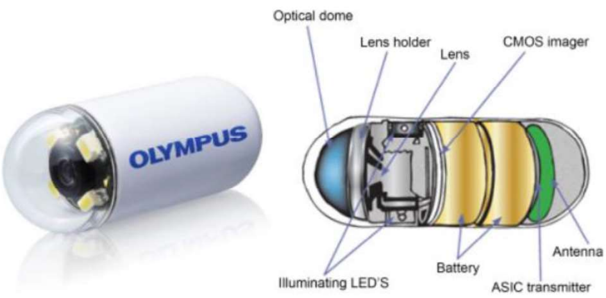

Figure 1.2 Cross section of a Wireless Capsule Endoscopy (9)

There are several antennas that have been tested for the application of WCE such as conformal antenna (12), spiral antenna (13), patch antenna (14), dipole antenna (15) and NMHA (16). A normal-mode helical antenna (NMHA) is selected as the subject antenna for this research. NMHA is small in size and high efficiency (17). Due to its small coil structure, antenna size is effectively reduced (18). Moreover, the coil structure produces two radiation sources such as electric and magnetic currents. Hence, high antenna efficiency is possible (19). High efficiency antennas are needed to ensure a communication link can be established (20–22).

WCE is a device used inside of the human body and has a receiver antenna outside of the human body. Methods for radio link design for application of WCE have been proposed by a number of papers such as (12-15). However, these papers did not focus on near field propagation and the methods proposed are used for far field transmission. For WCE that uses Medical Implant Communication Service (MICS) band as its operating band, the distance between the transmitter and receiver antenna is situated in near field region. Thus, near field link budget is more suitable compared to far field for this condition. In a nutshell, a new link budget equation based on the concept of Friis equation but for near field and in the human body is established in this research.

1.2 Problem Statement

Evaluation for link budget estimation in the near field region has been done by (7) and (8) but the evaluation is not done for application in the human body. WCE is a device that is implanted inside of the human body thus a radio link equation for in-body propagation is needed. On the other hand, analysis of link budget for near field transmission in the human body was done by (23–26) but the papers only provide the analysis and observation of signal propagation in the near field. A comprehensive equation for calculation of link budget is not provided in those papers. Thus, analysis and clarifying the important parameters for near field link budget design in the human body and validation of the equation through simulation is desirable.

The establishment of a suitable radio link budget for near field transmission is needed. In order to establish the near field radio link budget, a few important aspects need to be considered and achieved. These aspects include the matters on how to clarify the important parameters needed for near field radio link budget equations for WCE, how to analyse and express these parameters into equation from the changes in the electric field shown in the simulation and how to produce an analytical equation for near field radio link equation. These questions reflect the problems needed to be solve through this research in order to fulfil the requirement needed to the establishment of a near field radio link design of the receiver antenna for the application in Wireless Capsule Endoscopy.

1.3 Research Objectives

This research embarks on these objectives:

i. To establish an equation for near field radio link budget of NMHA in human tissues by clarifying important parameters through theoretical calculation.

ii. To compare the theoretical calculated values for radio link budget of NMHA in fat tissue with simulation in order to validate the values of power density, antenna equivalent area, power received and S_{21}

iii. To validate the equation by applying it on different tissues which are skin and stomach tissues.

1.4 Research Scope

This research is aimed to propose a radio link budget equation that can be used for NMHA when it is implanted inside of the human body with a receiver placed a few distance outside of the body. The scope of this research is highlighted as below

i. Identify the important parameters needed in the equation for estimating link budget in near field of NMHA in fat phantom. Identification is done by deducing an equation on radio link budget through calculation and considering important factors regarding signal propagation and transmission. Parameters that consider important are power transmitted (P_T), power received (P_R), efficiency of the antenna (η), dielectric loss (L_σ), transmission coefficient at the boundary (T), power spreading in free space (L_S), power density (W) and antenna equivalent area (A_e).

ii. Modelling of NMHA as the transmitter and receiver is done in the simulation software FEKO. Performance analysis through the simulation includes self-resonant structures, input impedance and efficiency for NMHA performance analysis. Through the simulation, near field distribution simulation analysis for power density and analysis of antenna equivalent area is done.

iii. Comparing the power received and S_{21} results obtained from calculation and simulation to evaluate the proposed equation for link budget design. Validate the equation by testing it using different tissues such as skin and stomach.

1.5 Significance of Study

Establishment of a suitable link design equation for Wireless Capsule Endoscopy system in the near field condition is important for precise design of WCE system. This is due to most of the application of WCE is in near field regions with low operation frequency. The derivation of the link design equation could improve the performance of WCE and improve the knowledge in signal propagation in the near field region. In this research, the designed equation is tested and validated in three different tissues such as fat, skin and stomach. Therefore, the proposed equation is suitable for the usage in fat, skin and stomach tissues.

1.6 Summary of Research Contents

The contents of the research are summarized in Table 1.1. The means for this research is divided into two which are simulation and calculation. By using the simulation software FEKO, transmitter and receiver antenna is modelled based on design proposed by (27) and (28). Near field distribution and power relation is analysed to clarify the factors that could affect link budget in near field propagation. Deduction of the equation for is done to clarify the parameters needed for link budget design through calculation. Comparison between simulation results and calculation results are done in order to check the validation of the proposed equation before the establishment of the final equation for link budget in the near field.

Table 1.1 Summary of research contents

Problem			Objective (Design principle)
Means	Subject	Contents	
Simulation	Transmitter and receiver antenna	Determine the antenna's self-resonant structure and efficiency in the human body (transmitter) and in free space (receiver).	Antenna design model by (27) and (28).
	Near field distribution	Checking the pattern and changes in power density	Analyzing the factors that could affect link budget estimation
	Power relation	Obtaining the value of power received and S_{21}	
Calculation	Deduce equation	Clarify the parameters needed for link budget in fat phantom	
		Analyse the changes in the power density and aperture area when distance increase	
	Comparison	Calculate the power received and S_{21} using deduced equation and comparing with the simulation	Establish the equation for link budget
	Validation	Testing the proposed equation with different tissues such as skin and stomach.	

1.7 Research Limitation

This research was done during the outbreak of the pandemic Covid19 throughout the world. Movement Control Order has been implemented in this country causes this research cannot be done in laboratory with proper equipment. Therefore, the fabrication and measurement of the antenna cannot be done. In order to fill in the gap of the limitations, more simulation results are presented in different situation for the purpose of validation.

1.8 Thesis Organization

This thesis is structured for five chapters. In Chapter 1 - Introduction gives the overall overview of the research. Research background, problem statements, objectives, research scope and significance of the research is presented in this chapter. Chapter 2 - Literature review explains the field region and the factors that would affect link budget in general. Review of previous research regarding link budget for the application of WCE is also presented. In Chapter 3 - Methodology, method in obtaining the link budget equation for NMHA is explained. Apart from that, simulation methods for electromagnetic software such as Method of Moments (MoM) are explained in detailed. Chapter 4 and Chapter 5 are presenting the results obtained through calculation and simulation. The results discussions are also done in these chapter respectively. Chapter 6 is the validation of the proposed equation with different tissues since the equation was designed based on fat phantom. Thus, validation is done for skin and stomach phantom. Chapter 7 is the conclusion part of this thesis. Summarization of the whole thesis is explained in this chapter. In this chapter also the contribution and suggestions for possible future directions are presented.

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