Near field radio link design in fat phantom for Wireless Capsule Endoscopy application

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Abstract. Medical devices such as Wireless Capsule Endoscopy (WCE) that need wireless imaging and monitoring, operating at 402 MHz, is considered to be in the near field region due to the distance being shorter than the wavelength. In this paper, the radio link calculation method in the near field region is investigated. Normal Mode Helical Antenna (NMHA) is used as the transmitter antenna which is placed inside of a fat phantom of 11.6 F/m and the receiver antenna at distance 0.1 to 1.0 m apart. For link budget establishment, parameters such as power density, W and receiver antenna effective area, A_e are investigated through electromagnetic simulation. The distance dependency of W is examined and the result of $W \propto 1/(\text{distance})^2$ is obtained. The relation of A_e of the receiver antenna is found to be the size of the cross-section area of the antenna. A radio link equation is formed by employing W, A_e and other propagation loss factors of a medium and is then compared with the power received, P_R and S_{21} obtained from simulation. The agreement between calculated and simulated results shows that this equation can be used in the near field region.

1. Introduction

Wireless Capsule Endoscopy (WCE) is one of the medical devices that has the purpose of diagnosing the health conditions inside the gastrointestinal tract. Evaluation of link budgets in the near field by [1] and [2] based on Friis equation and numerical evaluation using FEKO shows that the Friis equation is possible to use for the near field with some adjustment 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.

In this paper, analysis on power density and equivalent area at receiver antenna are analysed through electromagnetic simulation. The analysis is done in the near field region to check its adaptability. By using FEKO simulator software, the theoretical understanding about signal propagation can be compared with the simulation results to prove the hypothesis. Establishment of a suitable link design equation for WCE 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.

2. Near field link budget equation

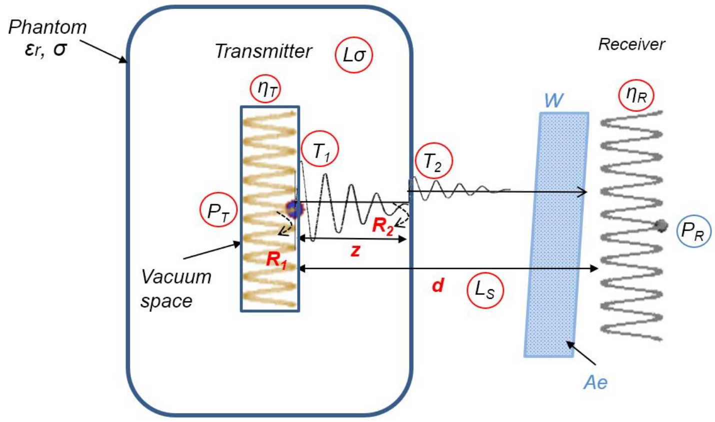

Figure 1. Signal transmission from transmitter to receiver

Figure 1 shows the illustration of signal transmission from NMHA inside a human body phantom to a receiver outside the phantom separated by distance, d. Based on the parameters deduced from figure 1, propagation link for transmission in the near field is proposed as equation (1). Based on equation (1), the parameters are received power (P_R), transmitted power (P_T), efficiency of the transmitter (η_T) and receiver antenna (η_R), transmitted signal from capsule to phantom (T_1), transmitted signal from phantom to free space (T_2), dielectric loss (L_σ), spherical spreading of power (L_S), and effective antenna aperture (A_e). Table 1 shows the descriptions of the parameters in equation (1).

$$P_R = P_T + \eta_T + T_1 + L_\sigma + T_2 + L_S + A_e + \eta_R \tag{1}$$

Table 1. Equations for link budget

Link Budget	Description of parameters	Expressed by equation
Transmitted power, P_T	Power transmitted	20 dBm (0.1 W)
Antenna efficiency, η	R_a, Radiation resistance R_{in}, Antenna input resistance	$\eta = 10\log\frac{R_a}{R_{in}}$ (2)
Transmission coefficient at the boundary, T	n, Refractive index of the phantom	$T = 10\log\frac{4n}{(n+1)^2}$ (3)
Propagation loss in phantom, L_σ	ε, Dielectric constant σ, Conductivity ω, Angular frequency α, Attenuation constant z, radius of phantom	$L_\sigma = 10\log e^{-2\alpha z}$ (4) $\alpha = \sqrt{\frac{\omega^2\varepsilon\mu_0}{2}}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)^{\frac{1}{2}}$ (5)
Power spreading in free space, L_S	d, Distance to the observation point	$L_S = 10\log\frac{1}{4\pi d^2}$ (6)
Effective area of the receiving antenna, A_e	W, Power density η_R, Efficiency of receiver antenna	$A_e = 10\log\left(\frac{P_R}{W\eta_R}\right)$ (7)

Efficiency of transmitter antenna, η is shown as equation (2) where R_a is the radiation resistance and R_{in} is the input impedance of the antenna. R_{in} is the pure resistance when NMHA reaches a self-resonant structure [3]. When signals propagate through one medium to another, reflection loss occurs. Parts of the signal waves are reflected back while some of it will be transmitted when signal travelled into a different material [4]. The relationship of transmission coefficient, T and reflected signal, R is shown as equation (3) where for T_1, $n = \sqrt{\varepsilon_r}$ and for T_2, $n = 1/\sqrt{\varepsilon_r}$. In this paper, the transmitted signals are considered to reflect twice; first from vacuum (inside the capsule) to the phantom layer, second from phantom layer to free space.

Dielectric loss can be calculated by using equation (4) where the thickness of dielectric medium, z and attenuation constant, α can be calculated using equation (5). The permeability of a biomedical materials, $\mu_r = 1$. Thus, μ is equal to μ_0. Based on the definition of power density at receiver, P_R can also be expressed as equation (6) where power density is W, antenna equivalent area is A_e and receiver antenna efficiency is η_R. From free space loss factor in Friis transmission equation, spherical spread of power exists to show the loss when the transmission distance increases. This equation can is shown in equation (8) [5].

Although theoretically equation (6) until equation (8) were mentioned by [5–8], analytical results to confirm these equations are not yet tested for NMHA in the human body for near field propagation. Clarification of L_S and A_e will strengthen the agreement of the proposed equation to be used to estimate link budget of NMHA in the human body.

3. Simulation of NMHA in FEKO

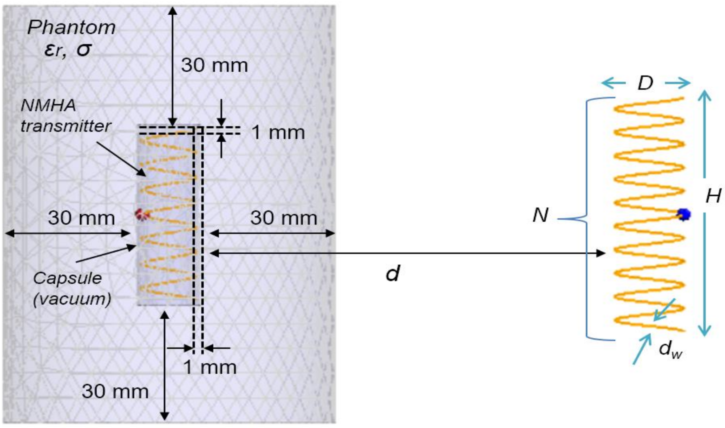

Figure 2. Model of NMHA in FEKO

Table 2. Parameter of transmitter and receiver antenna

Parameters	Transmitter	Receiver
Frequency	402 MHz (λ = 0.75 m)	
Material	Copper	
Wire conductivity, σ_w	$58\text{x}10^6$ [1/Ωm]	
Diameter of wire, d_w	1.2 [mm]	
Condition	Fat phantom	Free space
Dielectric constant, ε_r	11.6 F/m	
Conductivity, σ	0.1 S/m	
Height, H (mm)	43.8	59.7
Diameter, D (mm)	10.9	15.3
No. of turns, N	7	10
R_{in} (Ω)	25.0	2.99
R_a (Ω)	0.33	2.63
Efficiency, η (dB)	-18.76	- 0.56

A model of NMHA inside a human body phantom with a receiver antenna is simulated by using FEKO. The parameters for NMHA inside of human body tissues phantom model are shown in Figure 2. The size of the phantom is 30 mm from the transmitter antenna's dimension. Another NMHA as the receiver is added to the model. The distance between transmitter and receiver antenna is separated by the distance, d. The parameters for simulation are tabulated in Table 1. Diameter, height, number of turns and wire diameter are expressed as D, H, N and d_w respectively as shown in figure 2. Both transmitter and receiver antenna are designed according to self-resonant structure to ensure their efficiency. No polarization mismatch or impedance mismatch for both antennas.

4. Derivation of link design equation in fat phantom

4.1 Power spreading factor

Simulation software, FEKO is used to measure the value of W at each distance at 0.1 to 1.0 m from the transmitter. Power density is viewed in the near field distribution in order to check its pattern and magnitude when the distance of measured point increases. Figure 3 shows the results of power density at the distance of 0.1 m. The near field distribution results from figure 3 can be seen that the shape of the power density spreading is in spherical shape.

Power density, W can also be expressed in equation (8) where power transmitted is divided with the surface of a sphere. As shown in equation (8), the inverse surface of a sphere is considered as a power spreading loss factor. Power transmitted is constant for all conditions. The relationship between W and L_S is compiled in figure 4. Based on figure 4, the degradation pattern of W and L_S are the same. The results obtained for power density shows that power density decreases when the distance between transmitter and receiver increases. From the near field distribution, it can be seen that the power density spreads in spherical shape. Spherical spreading loss has the same degradation pattern as power density and come with the conclusion that $W \propto 1/(distance)^2$.

$$W = \frac{P_T}{4\pi d^2} \tag{8}$$

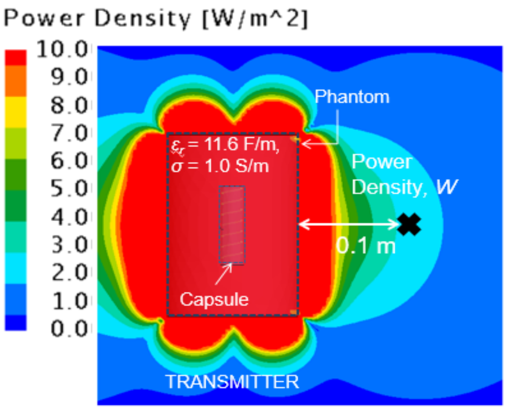

Figure 3. Power density separated by a distance of 0.3 m

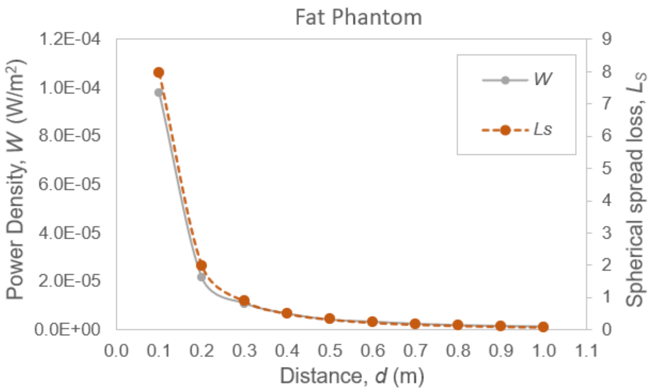

Figure 4. Power density and spherical spreading loss at different distance

4.2 Effective aperture of receiver antenna

Effective area, A_e can be calculated as equation (7). Figure 5 shows the comparison of effective aperture of receiver antenna with the structure of the receiver antenna. The data shown in figure 5 is the average value of A_e for distance 0.1 to 1.0 m. This shows that A_e has the value of 9.17 cm^2 which is almost equivalent to the surface dimension of the receiver antenna and no mismatching occurred here. Figure 6 shows the graph of calculated A_e using equation (9) with the value obtained from P_R and W. Based on Figure 6, the values of A_e is spreading near to the value of A_P which is the surface dimension of the receiver antenna. From the results show that A_e is almost as same as A_P. This leads to the conclusion where A_e can be calculated by using equation (7).

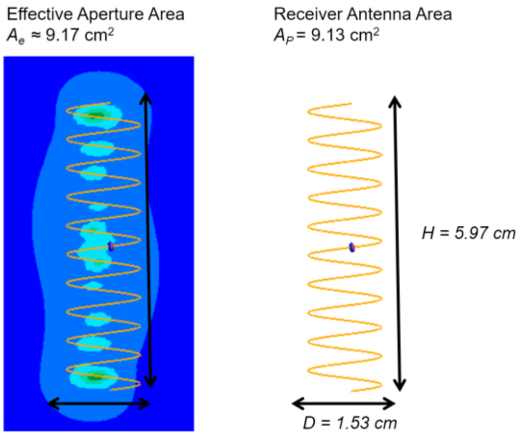

Figure 5. Comparison of effective aperture and antenna structure

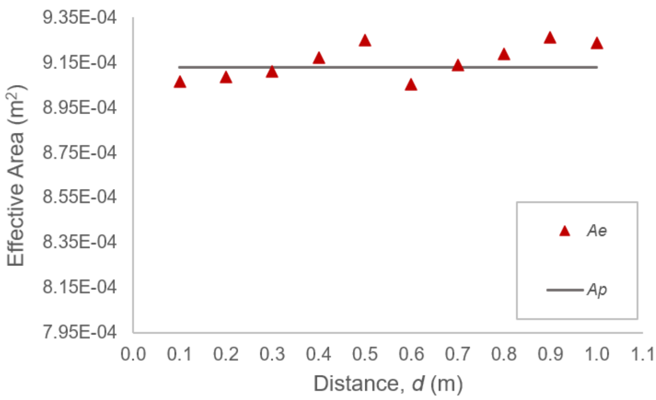

Figure 6. Effective area comparison for fat phantom

4.3 Comparison of Calculated S_{21} with Simulated S_{21}

In order to obtain the value of calculated S_{21}, P_R is divided with P_T as shown in equation (9). The results obtained from calculation using equation (9) are then compared with the simulation results obtained in FEKO software to ensure the agreement between them.

$$S_{21} = \frac{P_R}{P_T} \tag{9}$$

By using equation (1) and equation (9), power received and S_{21} for fat is calculated. The values of calculated parameters are tabulated in table 3. From table 3 P_T is kept constant at 20 dBm and other parameters such as η_T, η_R, T_1, T_2, L_σ and A_e are also constants. A_e is considered constant because the same receiver antenna is used throughout the distance until 1.0 m. The parameters that are affected by the increase in distance from the transmitter are L_S, P_R and S_{21} only.

Table 3. Calculated Parameters for Fat Phantom

P_T (dBm)	η_T (dB)	T_1 (dB)	L_σ (dB)	T_2 (dB)	A_e (dB)	η_R (dB)
20	-18.8	-1.54	-9.12	-1.54	-30.3	-0.56

***d* (m)**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
L_S (dB)	9.01	2.99	-0.53	-3.03	-4.97	-6.56	-7.89	-9.05	-10.08	-10.99
P_R (dBm)	-33.6	-39.8	-43.3	-45.8	-47.4	-49.4	-50.6	-51.8	-52.7	-53.9
S_{21} (dB)	-53.6	-59.8	-63.3	-65.8	-67.4	-69.4	-70.6	-71.8	-72.7	-73.9

From simulation, the results that can be obtained are P_R and S_{21}. The result for comparison between calculated S_{21} and simulated S_{21} is shown in figure 7. The graph in figure 7 shows that the equation used to calculate S_{21} of NMHA in fat phantom agree well with the simulation results obtained in FEKO software. This shows that the equation proposed for estimating radio link budget for NMHA in human body phantom is possible to be used for practice.

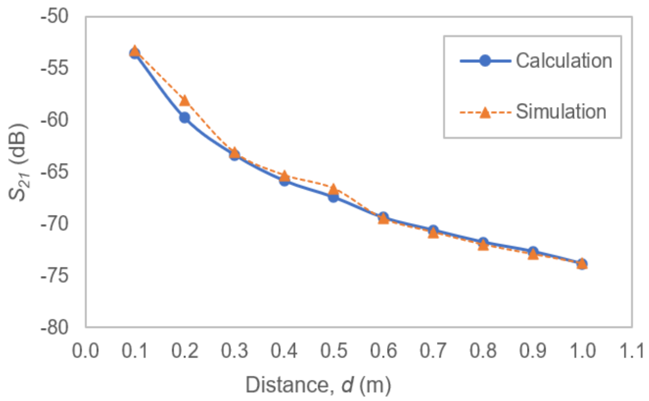

Figure 7. Comparison of calculated S_{21} with simulated S_{21}

5. Conclusion

The important parameters for radio link design in near field region are the power spreading in free space and the receiver antenna's received area which was employed for the NMHA. By the electric power density results calculated through the electromagnetic simulator, important parameters have been estimated. Through the results, it is clarified that the power spreading factor decreased by the square value of the distance. In addition, the results of the antenna equivalent area of the receiver antenna are almost the same as the cross-sectional area of the receiver antenna. The derivation of the radio link budget equation is completed after the analysis on the power spreading factor and antenna equivalent area were done. In order to prove the derivation of the proposed equation as an equation for estimation of link budget for NMHA, the calculated P_R and S_{21} is compared with simulation. From the comparison, it shows that the proposed equation can be used to estimate radio link budget for NMHA inside of the human body phantom.

6. References

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